



**RISK-BASED DECISION MODEL FOR DETERMINING THE  
APPLICABILITY OF AN EARNED VALUE MANAGEMENT SYSTEM IN  
CONSTRUCTION**

THESIS

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AFIT/GEM/ENV/06M-17

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## **Abstract**

New policy mandated by the Undersecretary of Defense for Acquisition, Technology and Logistics has lowered the dollar thresholds of contracts requiring earned value management (EVM). This policy directed that a “risk-based decision” be made to determine if EVM should be used on firm-fixed price contracts under \$20 million. Although not previously applicable to Military Construction (MILCON) building projects or other Air Force Civil Engineer (CE) managed contracts, the new threshold requires that CE projects be evaluated for risk.

Therefore, the focus of this research was to analyze the risk factors associated with construction contracts in an attempt to build a decision model to determine if EVM is warranted on the project. Due to the cost of implementing EVM, this model should probably be used only on Air Force construction projects with cost estimates over \$5 million. If the cost growth predicted by the model is greater than 5%, the use of EVM is recommended to monitor the risk factors. However, this recommendation should be tempered with the overall risk associated with a given project. In other words, if the calculated cost growth is high but the probability of occurrence is low, the decision-maker may want to forego the use of EVM and the associated costs.

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# RISK-BASED DECISION MODEL FOR DETERMINING THE APPLICABILITY OF AN EARNED VALUE MANAGEMENT SYSTEM IN CONSTRUCTION

## CHAPTER 1

### INTRODUCTION

Construction is not an exact science. Unlike a mathematical equation, there are factors associated with construction that are out of the control of the project manager but greatly affect the success of the project. In the construction business, success is typically measured by three basic performance criteria often called the triple constraint: cost, schedule, and quality. However, inherent in all construction projects are factors that influence these criteria and ultimately the success of the project. These factors are the many uncertainties associated with construction; they represent risk whenever a building is being built or renovated. There is risk to the owner due to their investment of capital; there is also risk to the construction contractor due to safety liability, failure of a sub-contractor, or owner default (Mustafa and Al-Bahar, 1991). A project manager must try to anticipate these risks in order to effectively mitigate their impacts. Without anticipation, the project manager is forced to put out the proverbial fires as they arise; however, it is usually better to be proactive than reactive. This is the challenge any project manager faces.

## **Background**

The heart of project management is the effective management of the competing interests represented by the triple constraint. Assuming quality is a direct result of the design, the project manager (PM) focuses primarily on the cost and schedule factors using a variety of tools. These tools are briefly discussed in the following sections before introducing the concept of earned value management.

### Construction Management

A project's success relies on three facets: design, cost and schedule. Construction management becomes involved after the design is complete. Therefore, management is typically concerned with a project's adherence to the budgeted cost and the proposed schedule. To control costs and schedule, many techniques are available to the project manager. Cost can be a function of a Work Breakdown Structure (WBS) using either a Schedule of Values or the Critical Path Method (CPM) (Fleming and Koppelman, 2002). The schedule can be shown through the use of a Gantt Chart in either the Program Evaluation and Review Technique (PERT) or using the CPM (Mantel et al., 2005). These methods are techniques used by project managers to ensure project success. However, Earned Value Management provides the project manager the most effective tool through the integration of cost and schedule (Christensen, 1998).

### Earned Value Management

The tools discussed above are extremely valuable to the PM; however, they look at cost and schedule as separate entities. Since cost and schedule are related, the concept

of earned value management (EVM) is becoming more widely used. EVM is a tool which helps the PM determine “the accurate measurement of physical performance against a detailed plan to allow for the accurate prediction of the final costs and schedule results for a given project” (Fleming and Koppelman, 2000). The EVM system has its roots in the Department of Defense (DoD), where it was used as early as the 1960s (Christensen, 1998). Its genesis was the Air Force’s establishment of cost/schedule planning and control specifications (C/SPEC) to set a standard, provide consistency, and properly manage the project management and administration system. The other military services implemented the concept and it became known as Cost/Schedule Control Systems Criteria (C/SCSC). It was not until the 1990s that industry adopted the concept, renamed it Earned Value Management System (EVMS), and established a formal process. The C/SCSC contained 35 management criteria that a contractor must meet to bid on government contracts. These 35 DoD criteria were then consolidated by industry into 32 criteria organized in five sections: Organization, Planning and Budgeting, Accounting, Analysis, and Revisions.

#### DoD Use of EVM

The use of EVM in the DoD is ubiquitous in the acquisition communities of all services. In fact, acquisition policy has established a threshold of \$315 million, above which EVM is mandated in contract requirements. The result is that many major weapon system contractors have become very familiar with its use. Fleming and Koppelman (2002) argue that EVM is just as useful and just as effective at mitigating risk on construction projects as it has proven to be on large weapon system contracts. To

increase the use of EVM throughout the DoD, a new policy, dated 7 March 2005, requires all contracts valued over \$20 million to use EVM. Furthermore, it also states that all contracts over \$50 million must require the contractor's EVM system to be validated. For contracts less than \$20 million, the policy states, "While not required, if a risk-based decision is made to require EVM..." it should be a contract requirement. Furthermore, it also states that all contracts over \$50 million must require the contractor's EVM system to be validated. For contracts less than \$20 million, the policy states, "While not required, if a risk-based decision is made to require EVM..." it should be a contract requirement. Presumably, the rationale for the risk-based approach is the implementation cost associated with EVM, which Christensen (1998) estimates ranges from 0.1% up to 5% of the total project cost. The upper limit is typically equal to the entire contingency fund on a construction project; therefore, EVM's use is not appropriate for all projects. However, no further explanations or criteria are provided to establish which risks should be considered. Therefore, the risk-based decision levied by the policy letter potentially impacts all contract management personnel.

### Risk

Project risk can be defined as the cumulative effect of the chances of uncertain occurrences adversely affecting project objectives (Wideman, 1992). Unfortunately, project risk is always present and unknowns are unavoidable. To be successful though, it is incumbent on the project manager to attempt to anticipate and mitigate these risks. The key is to understand the possible risks associated with a construction project and determine if a particular project has sufficient inherent risk to warrant EVM. In this way,

the project manager can institute procedures to mitigate the impact of a risk event when it occurs. Fleming and Koppelman (2002) may have summed it up best when they asserted that:

The basic utility of [an aggressive project management technique] is to contain the cost risks associated with projects. Bad news never gets better with time. The earlier you know that you have a problem on your project, the better chance you will have to mitigate that problem.

Given this brief introduction to risk, the problems and risk factors associated with construction can be addressed.

Although every construction project is different and contains its own risk factors, cost and schedule delays are typically a result of five overarching factors: physical attributes, design specifications, contractor, designer, and owner (Jeljeli and Russell, 1995). Physical attributes include differing site conditions, weather, technology, etc. Design specifications may include constructability issues, scope changes, accuracy of the design, and age of the design. The risks associated with the contractor are related to experience, past performance, and management. A designer or architect similarly brings risks due to experience, past performance, and proximity to the site. The reference to the owner is for lack of funds, which is typically not as much of a factor for government contracts.

Should unforeseen events occur, the PM must effectively manage these risks in order to limit the impact to the schedule and/or cost. To do this, the project manager has a contingency set-aside; however, this amount is arbitrarily set and generally calculated as a small percentage of the total project cost. The contingency fund allows the PM to avoid cost overruns to a certain point, but changes inevitably result in schedule delays.



Thus, the ability to integrate cost and schedule into one measure is the objective of earned value.

All projects have risk – to attempt a risk free project would not only be impossible but too costly and time consuming to implement appropriate risk avoidance techniques (Kendrick, 2003). So why do risk analysis? Kendrick (2003) puts it very succinctly:

Project risk management depends on thorough, sustained application of effective project management principals. The precise nature of the project management methodology can vary widely, but management of risk is most successful when consistent processes are adopted by the organization as a whole, because there is more information to work with and more durable support for the ongoing effort required.

It is this management of risk that comes full circle back to the DoD's policy regarding a "risk-based decision" and the use of EVM. Therefore, it is imperative that a quantitative method be developed to accurately assess the specific risks associated with construction projects.

### Air Force Concerns

Within the DoD, the Air Force (AF) experiences similar problems related to managing risks and minimizing the impact on cost and schedule delays. For instance, the proposed Air Force military construction (MILCON) budget in fiscal year (FY) 2006 is \$4.7 billion. Since the AF's goal is to manage construction cost growth to 5% or less of the original contract amount, the contingency fund reserved for MILCON projects could amount to \$235 million. Therefore, it is imperative that AF construction project managers anticipate risk factors and implement aggressive project management techniques to mitigate these factors. Currently, the AF relies on the Army Corps of

Engineers to manage MILCON projects; however, the AF project manager must still deal with the budgetary constraints and the impact of cost overruns and schedule delays.

### **Problem Statement**

The policy letter and the associated rationale reference the need to perform a “risk-based” assessment in order to determine if EVM is warranted on contracts less than \$20 million. Therefore, this research will attempt to help the project manager by building a decision model to evaluate the risks associated with military construction projects and provide a quantitative analysis to determine whether EVM should be used on a particular construction project. Therefore, the question that arises is how to assess the risks associated with AF construction projects in order to determine if sufficient uncertainty exists to warrant EVM.

### **Research Objective**

The objective of the research is to develop a model, which evaluates risk factors associated with construction, the risk’s associated probability of occurrence, and the subsequent cost growth impact. The model will yield an expected cost growth, which will then be used to determine whether EVM should be recommended. The ensuing investigative questions addressed during this research are listed below.

1. What risk factors affect the cost or schedule of Air Force construction projects?
2. What is the probability of occurrence of the identified risk factors?
3. What is the subsequent cost growth due to the occurrence of the risk factor?

4. How many Air Force construction projects accomplished in the last 5 years and those programmed through the FY12 exceed the \$20M threshold or fall into a range which must be evaluated?

## **Methodology**

The following decision analysis methods were used to quantify the risk, probability, and cost growth associated with construction: Alternative-Focused Thinking (AFT), Value-Focused Thinking (VFT), Influence Diagrams, and Decision Trees. Although AFT and VFT are excellent at breaking down a decision into its component elements and evaluating alternatives based on a decision maker's preferences, the limitation is that the resulting values are not scalable to each other. In other words, there would be no way to evaluate a construction project's risk and compare it to an established project that warrants EVM. Influence diagrams are very useful because they establish a visual representation of the interaction between factors affecting a decision but fall short in the analysis of the "chronological structure and state of uncertain events" (Jeljeli and Russell, 1995).

The decision tree model allows for the exploration of as many of the risk factors as possible. The decision tree provides the breakdown of the component elements of a decision, integrates uncertainty, and yields an outcome which optimizes the expected value (Clemen and Reilly, 2001). The model will attempt to anticipate all possible outcomes resulting from the unknowns related to any construction project, such as weather delays, unforeseen sight conditions, problems related to renovation versus new construction, pitfalls of a design-bid-build contract versus a design-built type of contract. The decision tree will in this respect explore all possible risk scenarios to yield a factor of

growth of the project cost. Based on this cost growth the decision maker will have additional insight regarding the appropriateness of using EVM to manage the project risk.

### **Assumptions and Limitations**

Several assumptions and limitations are relevant for this research. The primary assumption is that the revised DoD EVM policy letter dated 7 March 2005 is applicable to Air Force construction contracts. Additionally, this research assumes that the risk-based decision called for in the revised policy letter requires more than a subjective evaluation by a decision maker. The primary limitation affecting this research is with respect to the accuracy of the data used to build the model. Although cost growth data is contained in the Automated Civil Engineer System (ACES), this thesis will focus on the use of expert opinion to provide quantifiable data. A limitation associated with expert opinion is that it may be subject to biases and influences not easily controlled. Therefore, the results will be subject and open for interpretation and disagreement but the data acquired is assumed to be true and accurate.

### **Significance of Study**

The requirement to assess the risks associated with construction projects because of the revised DoD EVM policy is new. The standard practice is to assign a 5% contingency amount to construction projects to cover unforeseen events. The revised policy requires that a decision be made based on the risk in order to determine the applicability of EVM to the project. The significance of this research is that it will

provide a quantifiable process for determining the level of risk associated with a specific construction project to make an informed decision about the applicability of EVM.

### **Organization of Remaining Chapters**

The subsequent chapters will cover the relevant literature, the methodology, the results and finally the conclusion of this research. Chapter 2 details the literature applicable to construction management, earned value management, risk, and decision analysis. Chapter 3 covers the methodology used in this research; it focuses on the Delphi method and the use of decision trees. The results will be analyzed and explained in Chapter 4. The final chapter will discuss the conclusions reached from this overall research effort.

## CHAPTER 2

### LITERATURE REVIEW

Chapter 2 provides detail into the relevant subject areas that this research utilizes. The recent literature in the areas of construction management, earned value management, decision analysis, and risk analysis is reviewed. The first section discusses construction management and specifically focuses on the techniques to monitor a project's cost and schedule. A specialized method of tracking project cost and schedule, Earned Value Management (EVM), is covered as well. Decision Analysis (DA) techniques such as Alternative-Focused Thinking (AFT), Value-Focused Thinking (VFT), Influence Diagrams, and Decision Trees are then discussed. Finally, the concept of risk is discussed in terms of its fundamentals, management, and existing research in construction risk assessment.

#### **Construction Management**

All project managers (PMs) deal with the three factors affecting any construction effort: design, cost, and schedule. Often, the design is already established; therefore, the only control over the project's success or failure is the effective management, oversight, and control of the project's cost and schedule. The original cost estimates are typically used to develop the project budget, which then serves as a road map for the expenditure of money related to each phase of the construction. The accompanying schedule is generally based on either time or resource constraints. Time-based scheduling refers to a critical path method in which completion of one phase is required before the next phase

can begin. Resource-based scheduling is based on the necessity of manpower, equipment, and materials to accomplish the construction (Hendrickson, 2003). The PM has multiple tools available to monitor cost and schedule.

### Monitoring Cost

Since Hendrickson (2003) states that the “original detailed cost estimate is typically converted to a *project budget*,” the budget is often considered the primary tool to monitor cost. Using the delineation of work represented by the detailed cost estimate, each element of work thus has an associated cost and is typically assigned to a cost account. These cost accounts begin at major division levels such as site preparation; foundations; heating, ventilation, and air conditioning (HVAC); electrical; mechanical and so forth with sub-divisions which break down each major division into the smallest possible element that can be tracked (Hendrickson, 2003). The final product is a Work Breakdown Structure (WBS) that represents all tasks for a given project. The WBS is typically shown graphically as a tree with each branch delineating major divisions and expanding further to show work elements (Mantel et al., 2005). Since the WBS is strongly related to the cost estimate, tracking expenses versus the planned work allows for an objective assessment of cost accounting. Figure 2.1 shows a WBS from the work breakdown and the cost accounting view.

# Work Breakdown Structure

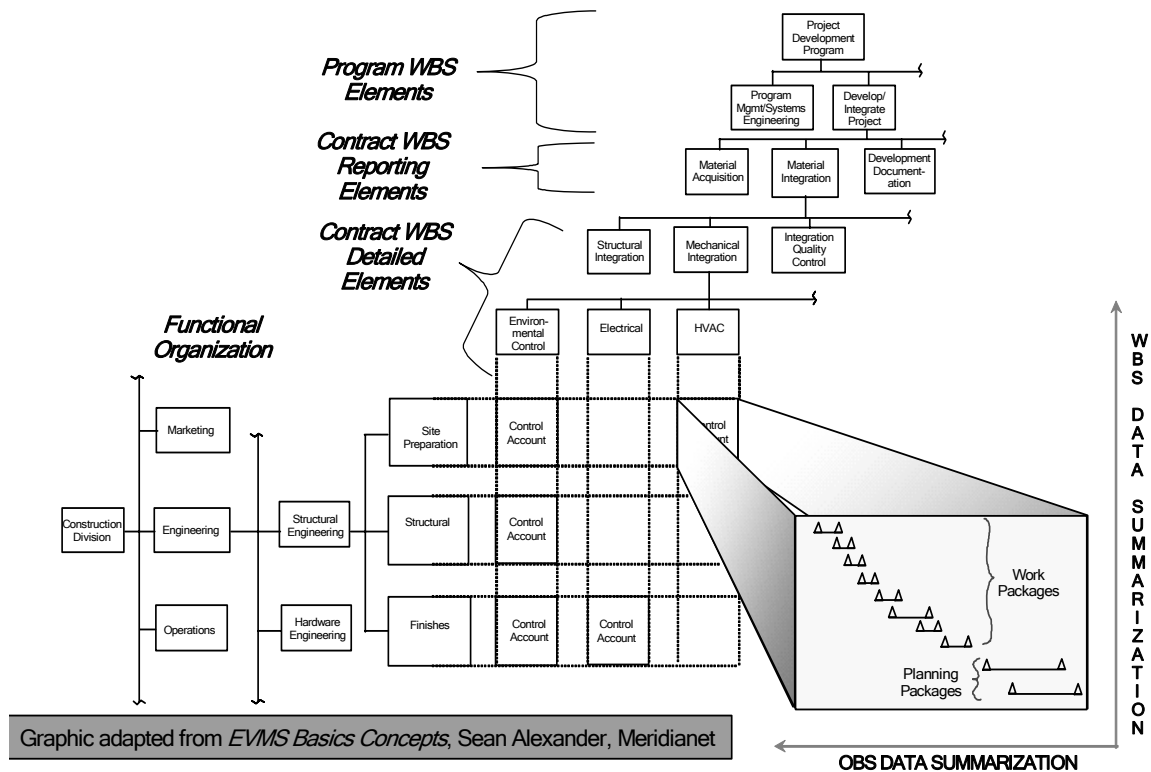


Figure 2.1 Work Breakdown Structure (Stockman, 2006)

As work progresses, the contractor submits invoices that reflect the materials and labor expended to accomplish the individual work element. However, complicating factors are inevitable; as the project experiences scope changes, unforeseen sight conditions, weather delays, or any number of other complications, actual costs will deviate from the budget. Therefore, the PM must incorporate cost control tools to



adequately track the variance between actual cost outlays and the planned budget. Two methods of controlling costs are the Schedule of Values and Critical Path Method (CPM). The Schedule of Values is a line-by-line accounting of the work to be performed and the costs associated with the work. As the project progresses, the PM can itemize the line items being billed and track the work versus the project budget (Fleming and Koppelman, 2002). Although CPM is primarily used for scheduling, it can also be used for costs if the specific costs are attributed to the individual work packages shown in the CPM (Fleming and Koppelman, 2002).

The PM can also use the cost accounts from the WBS to effectively manage cost variances. For example, the labor required to install the electrical outlets in a room on a particular floor could be the lowest sub-division on a WBS. Therefore, if twice as much labor is required to perform the work than initially budgeted, the PM is able to track the incremental cost growth of the labor. In this way, the PM is able to monitor cost but has little control over preventing such occurrences. Similarly, if the work takes twice as long to perform than originally estimated, the PM is able to track the impact on the project schedule.

### Monitoring Schedule

The primary tool in schedule management is the project baseline (Fleming and Koppelman, 2002). The first attempt to quantify the project was the Gantt chart, which was developed in 1917 in an effort to identify graphically all the steps required to complete a project. The benefits of the chart are that the work is broken down into specific work elements and the entire project is shown as a progressive iteration of work

packages. The limitation, however, is when multiple tasks have concurrent start times and similar durations. The overlapping start times and finish times reduce the effectiveness of the technique because the sequence of tasks that drive the schedule are indistinguishable in the chart from those tasks which are independent of the critical path (Mantel et al., 2005).

Based on the Gantt chart, the most common standard formats for monitoring the project baseline are the Program Evaluation and Review Technique (PERT) and the Critical Path Method (CPM). These techniques were developed independently in the 1950s and depend on the order and sequence of the work to be accomplished. Each method tracks task completion, which is considered to be dependent and/or contingent on the success of a previous task or a set of tasks. For example, if a task is not completed on time, it creates delays in succeeding tasks and the entire project if it is on the critical path (Mantel et al., 2005).

Although the distinction between PERT and CPM is trivial in execution when managing a project baseline schedule, the methods differ greatly. PERT employs probabilistic estimates based on the uncertainty associated with task durations, while CPM assumes 100% certainty in time estimates to develop deterministic task durations. Despite the differences in methodology, the symbolic nature of the PERT and CPM techniques eliminates the ambiguity of concurrent tasks in the Gantt chart by focusing on the technical details. These methods integrate the graphical nature of the Gantt chart with the technical details pertaining to each activity. The details included are activity name, activity duration, earliest start time (EST), earliest finish time (EFT), latest start time (LST), latest finish time (LFT), and slack (Mantel et al., 2005).

Regardless of the method chosen, the project manager uses these techniques only to monitor schedule progress and not to affect change. To affect change, critical knowledge of a project must be obtained regarding the combined effect of both cost and schedule progress. The analysis of the link between cost and schedule, often referred to as earned value management, provides the most powerful tool to control future cost and schedule growth (Christensen, 1998).

### **Earned Value Management**

Earned value management (EVM) is a management tool that allows for the integration of a performance schedule with a monetary outlay, or payment schedule. To gain a better understanding of EVM, the rest of this section discusses its history and key components. Additionally, the cost of implementing EVM and its applicability to the construction field are discussed.

#### History

The concept of EVM has its roots in the Department of Defense (DoD). As early as the 1960s, the DoD was using the concept of earned value as a way to compare planned work versus completed work (Christensen, 1998). The Cost/Schedule Planning and Control Specifications (C/SPEC) Group was created by the Air Force to generate standards and measures by which contractors were evaluated before being awarded large contracts (Smith, 2005). To properly manage the concept, specifications were identified to quantify the standard measurement among companies who wished to bid on government contracts. These specifications laid out a systematic management control

function that contractors were required to have, use, and maintain to update project cost and schedule progress. The C/SPEC also provided consistency in the calculation and evaluation of cost and schedule factors, equations, and results, which form the basis of EVM. Ultimately, these specifications evolved into the Cost/Schedule Control Systems Criteria (C/SCSC), which subsequently became the standard within DoD (Christensen, 1998).

It was not until the 1990s that industry adopted the concept, renamed it the earned value management system (EVMS), and established a formal earned value process. Industry reorganized the previous DoD criteria and categorized 32 criteria into five sections: Organization, Planning and Budgeting, Accounting, Analysis and Management Reporting, and Revisions and Data Maintenance. The DoD quickly implemented these revised criteria as the new government standard. These criteria were subsequently adopted in 1998 as the American National Standards Institute/Electronic Industries Alliance Standard 748, Earned Value Management Systems (ANSI/EIA-748). Thus, in almost 50 years, EVM has developed from a concept used primarily in the military to an industry standard.

### Components

To track a project's progress against the baseline plan, three key components must be understood: Planned Value, Earned Value, and Actual Costs. Planned Value is the cost estimate at the beginning of the project based on the project baseline, otherwise known as Budgeted Cost of Work Scheduled (BCWS). The second factor is Earned Value, which is tracked during execution of the project and represents the cost of the

work that has been authorized and completed (also known as Budgeted Cost of Work Performed (BCWP)). The third factor, Actual Costs, represents the “actual costs incurred to convert the Planned Value into the Earned Value” and is typically known as the Actual Cost of Work Performed (ACWP) (Fleming and Koppelman, 2002). Using these factors, a project manager is able to calculate several other parameters and indices of interest, which help provide a better understanding of a project’s performance.

### Project Performance

The Performance Measurement Baseline (PMB) integrates the project baseline and the cost associated with each element; it is the standard by which the project is compared from start to finish. The difference between the PMB and the actual cost expenditures updated continuously throughout the project is measured two ways. The first is related to cost and the second is associated with schedule. Cost Variance (CV) is calculated by subtracting the ACWP from the BCWP. The result indicates whether the project is costing more or less than the PMB at a given time during the project. A negative value indicates that the project is over budget, while a positive result means the project is under budget (Mantel et al., 2005). Schedule Variance (SV) is calculated by subtracting the BCWS from the BCWP. The result indicates whether the project schedule is ahead of or behind the PMB. A negative value indicates that the project is behind schedule, while a positive result means the project is ahead of schedule (Mantel et al., 2005).

In addition to these parameters, performance indices are used to determine the status of a project and calculate the expected project completion date and final cost

(Stockman, 2006). These performance indices are comprised of three factors: Cost Performance Index (CPI), Schedule Performance Index (SPI), and Cost Schedule Index (CSI). The CPI, calculated by dividing the BCWP by the ACWP, represents the ratio of work accomplished versus the cost to accomplish the work; it is often called a cost efficiency rate. If the ratio is greater than one, it indicates that more than a dollar's worth of work was accomplished for every dollar spent. A ratio less than one shows that it is costing more to do the work than the baseline projected. In a study of over 700 DoD projects, the CPI was found to stabilize by the time a project was 20% complete. In fact, the study indicated that the "percent overrun at completion will be within 10% of percent overrun at 20% complete" (Fleming and Koppelman, 2002). This means that a final project cost can be forecasted within 10% as early as 20% into the project. Similar to the CPI, the SPI is calculated by dividing the BCWP by the BCWS. It represents the ratio of work accomplished versus the value of the planned work. If the ratio is greater than one, it indicates that the cost of work completed is greater than the planned amount; a ratio less than one shows that the cost of work completed is less than the planned amount. The third factor, CSI, is calculated by multiplying the CPI and the SPI. The results are a combined index of the cost and schedule performance.

Once these indices are calculated, additional information about the project can be calculated. The project completion estimates are Estimate to Complete (ETC), Estimate at Completion (EAC), and Variance at Completion (VAC). The ETC is the difference between the Budget at Completion (BAC) and the BCWP divided by the CPI. It applies the observed cost efficiency to estimate the cost to finish the remaining work. The EAC is simply the ETC plus the ACWP, and the VAC is the difference between the BAC and

the EAC. The VAC shows how much over (or under) budget the project is estimated to cost. Figure 2.2 graphically shows the performance indices and their relationship to the original estimate, which is the PMB.

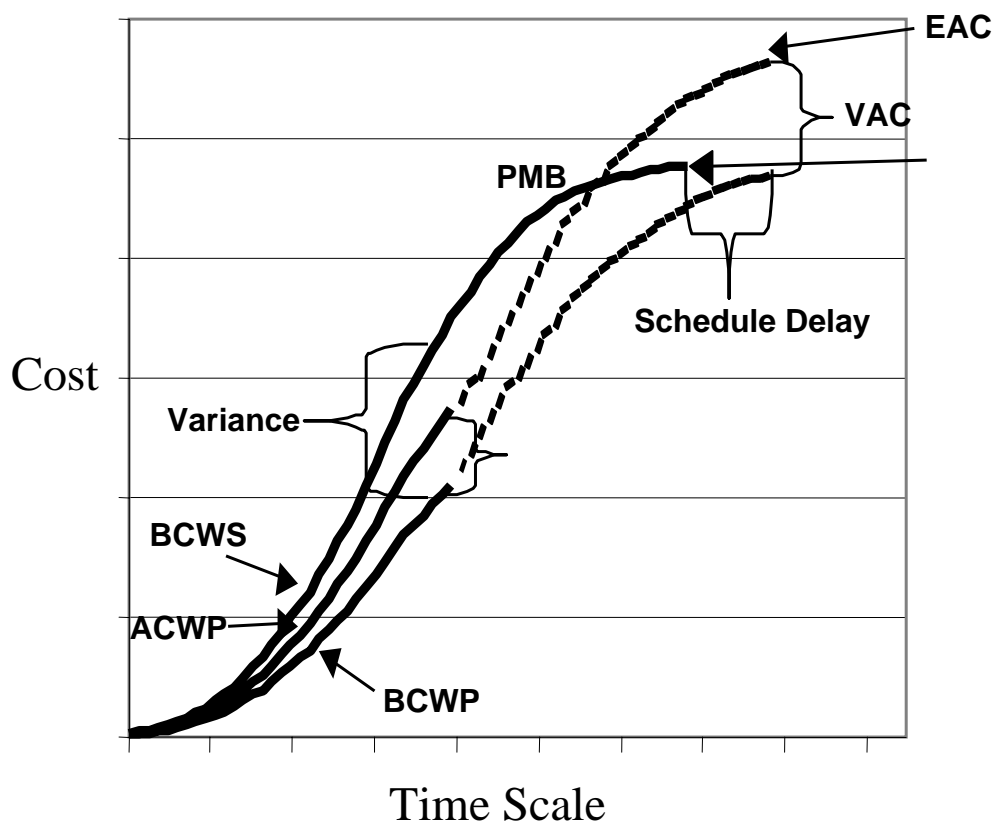


Figure 2.2 Earned Value Performance Indices (Stockman, 2006)

### Cost of EVM

The benefit and power of EVM does not come without costs. In an analysis of six studies done on the cost of EVM across industry and the DoD, it was found that the cost of EVM could range from as little as 0.1% up to 5% of the total project cost (Christensen, 1998). Therefore, EVM has traditionally been used on large cost-reimbursable contracts for major DOD weapon system development and purchase where the cost of EVM is far exceeded by the benefits attributed to project management and oversight.

### Construction Applicability

The upper limit of EVM cost (i.e., 5%) is equal to the entire contingency budget of a typical Air Force construction project; therefore, EVM has not been used in the construction field. However, Fleming and Koppelman (2002) contend that EVM is warranted for construction projects and propose six recommendations.

- Require the construction contractor to provide a “time-phased Schedule of Values in which the sum of the line items will add up to the total contract value.” This can be thought of as the Planned Value or BCWP. In terms of construction, this resembles a Gantt chart in which the costs associated with each work package are integrated with the chart.
- Require the construction contractor to provide monthly invoices of actual costs incurred and to update the Schedule of Values with current progress. This provides the BCWP and ACWP values necessary to calculate cost and schedule variance.



- Calculate and compare the Schedule Performance Index (SPI) and the Cost Performance Index (CPI) not only as a gauge for an individual project but also as a means to compare projects from an enterprise view.
- Calculate the estimate for final cost and determine if that value exceeds the owner's risk.
- Require suppliers of the contractor to provide a "time-phased schedule of value." Shown graphically, this should resemble an S-shaped curve to reflect a gradual build-up of inventory, transitioning to a more rapid build-up, and then a slow decline at the end of a project. Something other than an S-shaped curve would be a warning sign.
- Require the contractor to track payments to suppliers. This recommendation is designed to monitor and avoid contractors experiencing loss due to a differential between what has been forecasted and what is actually paid to suppliers.

The effect of these recommendations is the mitigation of risk, which should be a goal of all project managers. All construction has risk, but the ability to forecast or anticipate risk prevents excessive cost and schedule overruns and thus provides for a more successful project.

### **Earned Value Management in the DoD**

Prior to March 2005, DoD directives established two thresholds for using EVM. The first applied to contracts related to Research, Development, Test, and Evaluation (RTD&E) and required EVM on projects greater than \$73 million. The second applied to Procurement/Operations and Maintenance (O&M), which includes construction projects,

and required EVM on contracts greater than \$315 million. In March 2005, the DoD revised its policy regarding the use of earned value management. The revised policy (see Appendix A) established a uniform threshold for all contracts of \$20 million and included six recommendations, which significantly alter the EVM system used by the DoD to manage large contracts.

This research is specifically relevant to recommendation number six, which deals with the requirement to perform a risk analysis on contracts to determine if EVM would benefit the project management. The text of this recommendation is as follows:

The application of EVM on cost or incentive efforts, including contracts, subcontracts, intra-government work agreements, and other agreements valued at less than \$20M is optional and is a risk based decision that is at the discretion of the program manager. A cost-benefit analysis shall be conducted before deciding to implement EVM in these situations. (DoD EVM Policy Letter, 7 March 2005)

To clarify the broad changes, a policy letter (included as Appendix B), was issued in October 2004. Included in the letter are five recommendations that “aim to simplify, improve, and increase consistency in DoD EVM policy and processes... [and] ...is a reflection of modern day EVM best practices aimed at bringing EVM within DoD into the 21<sup>st</sup> Century.” Among the five recommendations, the fifth recommendation is the applicable point for this research and it states: *EVM for all firm fixed price contracts, subcontracts, intra-government work agreements, and other agreements will be a risk-based decision* (DoD EVM Policy Letter, 7 March 2005). However, a risk-based decision requires the need to define the risk and then establish a decision process to evaluate the identified risk factors associated with an AF fixed-price construction project.

## **Decision Analysis**

In order to provide a decision maker with quantitative methods for exploring all aspects of a decision, Decision Analysis (DA) is a broad field of study which provides multiple techniques to help a decision maker consider all aspects and possible outcomes in order to make a more informed decision (Clemen and Reilly, 2001). DA does not make the decision; it structures the question, considerations, and options so that the decision maker has as much available insight and information as possible. When considering DA's breadth of use, Arsham (2006) states, "Decision analysts provide quantitative support for the decision-makers in all areas including engineers, analysts in planning offices and public agencies, project management consultants, manufacturing process planners, financial and economic analysts, experts supporting medical/technological diagnosis, and so on and on."

### DA Concepts

Although DA often evokes thoughts of probabilities and statistics along with complex uncertainty, the basic concept is to structure the decision into manageable tasks or sub-decisions. Figure 2.3 helps explain the process, showing steps that range from understanding the decision and its objectives through analysis and implementation (Clemen and Reilly, 2001). The uncertainty that DA attempts to explore is based on empirical data in the form of past records, statistics, observations, or experimentation. However, if no empirical data for objective probabilities exists, decisions must then be based on subjective probabilities (Haimes, 2004). Additionally, DA relies on multiple techniques to explore the elements, nuances, and possible outcomes of a given decision.

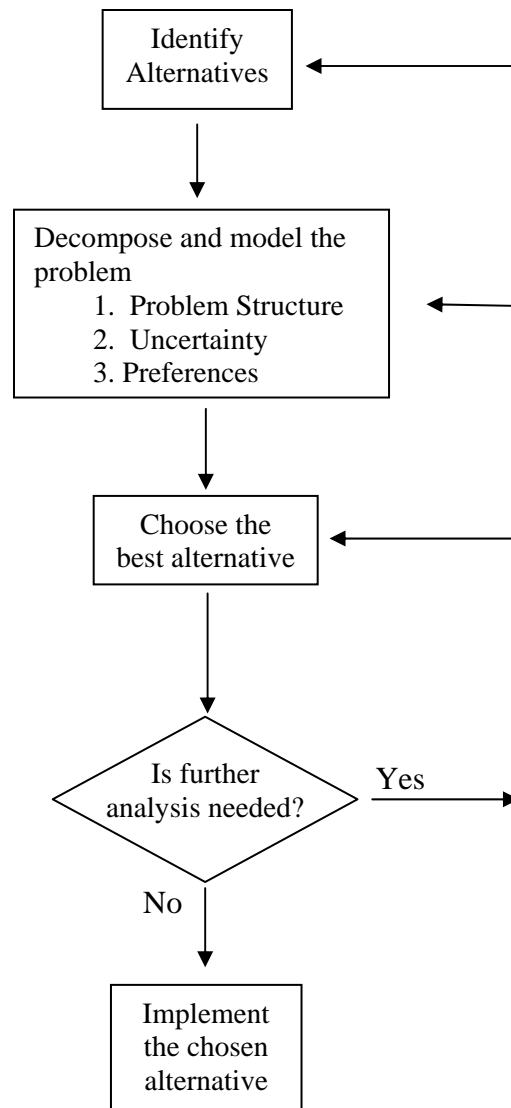


Figure 2.3 Decision Analysis Process Flowchart (Clemen and Reilly, 2001)

## DA Techniques

Determining what is important and how the decision maker's choices rate versus those important criteria are the two building blocks of decision analysis (Kirkwood, 1997). DA is considered to be "both a technique for probabilistic analysis and a tool for exploring and evaluating alternative courses of action" (Ashley, Stokes, and Perng; 1988). The techniques available to conduct DA vary according to the decision and the approach taken to evaluate the decision. If the focus is on alternatives, either Alternative-Focused Thinking or Value-Focused Thinking would best serve the decision-maker. If the decision relies on distinct relationships between factors and considerations must be made for the sequence or order of the factors, influence diagrams are the most appropriate technique. However, if the analysis must consider multiple decisions and includes chance events, a decision tree provides the greatest power to evaluate and explore all branches of the decision (Clemen and Reilly, 2001). Each of these techniques is discussed in more detail in the rest of this section.

Alternative-Focused Thinking: Alternative-Focused Thinking (AFT) is a technique that allows the decision maker to rate the alternatives based on the Decision Maker's (DM) assessment of the differences between the alternatives. AFT requires that the decision be looked at in terms of the choices available. Once the alternatives are chosen, each one is evaluated based on the same set of criteria to determine which alternative best meets the decision-maker's criteria. This technique is often used when the alternatives are established and the criteria are well defined. A prime example would be the decision to buy a new car. The alternatives are simply the cars the DM is interested in buying. The AFT methodology uses the DM's preferences to evaluate and

rank order the cars based on the value given to price, color, engine, size, gas mileage, etc. The result is a rank ordering of the cars considered and a top choice that maximizes the value structure. The problem arises when the best alternative is not among the alternatives evaluated. Therefore, AFT simply solves the problem by just looking at the apparent choices and picking the best of what is available (Keeney, 1992).

Value-Focused Thinking: Value-Focused Thinking (VFT) is very similar to AFT. However, instead of evaluating alternatives based on a DM's distinction of the alternatives, the VFT process starts out by asking the DM to establish the criteria that are most important in the decision. For VFT, the process starts with the best and works to make it a reality with the decision (Keeney, 1992). Once the decision problem has been identified, the decision-maker is asked to establish a value hierarchy, which forms the set of criteria for evaluation. This process provides unique insight into the decision-maker's values and helps identify the important aspects of the decision. The result is that the criteria influence the alternatives rather than the proposed alternatives driving the criteria (Katzner, 2002). The resulting VFT model evaluates the possible decision alternatives based on the value hierarchy and returns a ranking of the alternatives. In the new car example, VFT would establish the value hierarchy of decision criteria such as price, color, engine, size, gas mileage, etc., before any cars are evaluated. Unfortunately, the result is simply an ordering of the alternatives and cannot be compared or evaluated to a standard or to each other. This is the primary limitation of VFT and is the reason it is not applicable to this research (Weir, 2005). This research evaluates each project individually and compares it to a standard, which is not conducive to VFT methodology.

Influence Diagrams: Another decision analysis technique available to a decision-maker is the influence diagram. Influence diagrams are very useful because they establish a visual representation of the interaction between factors affecting a decision but fall short in the analysis of the “chronological structure and state of uncertain events” (Jeljeli and Russell, 1995). Used often to evaluate investment alternatives, influence diagrams create an effective illustration for computer analysis; they also depict relationships between decisions and risk, as well as provide a clear characterization of probabilistic interdependencies (Ashley et al., 1988). However, influence diagrams have many pitfalls, such as confusing them with flow diagrams and a tendency to build a circular path in the diagram (Clemen and Reilly, 2001). These pitfalls and the inability to adequately explore all the risk scenarios of an USAF construction project make the influence diagram inappropriate for this research.

Decision Trees: Decision trees are similar to influence diagrams but provide a much greater level of detail into the possible outcomes (Clemen and Reilly, 2001). They provide a breakdown of the component elements of a decision, integrate uncertainty, and yield an outcome; this allows for the optimization of the expected value, thereby exploring all possible risk scenarios associated with the uncertainty (Jeljeli and Russell, 1995). The power of a decision tree is to integrate multiple decisions and multiple chance events into a single structure; when solved, it yields a result that considers the probability and outcome of the options of a chance event and considers the benefit of each choice in the decision. The other benefit of a decision tree is the ability to overcome the limitation of sequence or order of chance events (Clemen and Reilly, 2001). Unlike influence diagrams, the order of events does not affect the outcome of the result (Clemen

and Reilly, 2001). Decision trees are used for a variety of decisions, such as whether to invest in a risky stock venture to the likelihood of a hurricane hitting a certain area and the decision whether to evacuate or stay. The limiting factor of a decision tree is that with multiple chance nodes and multiple outcomes the exploration of every possible outcome grows the tree exponentially (Weir, 2005). For instance, a tree with 4 sequential chance events and 3 possible outcomes per event results in 81 ( $3^4$  power) branches. By adding 2 more chance events, the number of branches grow to 729. Due to the nature of construction risk factors and variability, a decision tree's ability to evaluate multiple levels of risk for each chance event lends itself best to this research.

Decision Analysis Summarized: Regardless of the technique, DA allows for the exploration of various facets of a decision. Whether the technique is considering the DM's values or investigating the possible outcomes of chance events, DA provides the DM with additional insight into the decision and the choices to be made. In this research, the chance events are based on risk and the analysis of those factors, which can affect the outcome (i.e., the decision). The power of DA is the development of a cumulative risk profile of the factors, which shows the possible outcomes and expected value, thereby providing insight into the decision (Kirkwood, 1997). As such, the next step is to understand the risk related to construction projects.

## **Risk Factors**

Risk is simplistically described as uncertainty; if everything were known about a project, there would be no risk. To be more precise though, risk has two distinct elements: the potential loss due to the risk coupled with the likelihood of the risk



(Kendrick, 2003). EVM can identify cost and schedule problems in a project, so what remains is the question of what makes a construction project risky. This is the key issue that this research will attempt to identify and quantify. Therefore, a model is necessary that will evaluate construction projects to determine the level of risk or uncertainty associated with it and determine whether EVM is an appropriate tool to use to monitor and control those uncertainties.

### Fundamentals of Risk

Merriam-Webster (2006) defines risk as, “the possibility of loss or injury, someone or something that creates or suggests a hazard, or the chance of loss or the perils to the subject matter of an insurance contract; *also*: the degree of probability of such loss.” Relating this to construction risk, Smith and Merritt (2002) state that risk is “the possibility that an undesirable outcome-or the absence of a desired outcome-disrupts your project.” Decision analysis may relate risk more to the analytical definition of risk as “a measure of the probability and severity of adverse effects” (Haimes, 2004). Taking these definitions into consideration, this research must identify those factors, which create risk, determine the cost impact of those factor’s effects, and quantify them in relation to construction projects.

### Managing Risk

Risk management can be defined as “the art and science of identifying, assessing and responding to project risk” (Wideman, 1992). Although there are many approaches and techniques to risk management, a top-level look would divide the field into micro

and macro. Micro risk management deals with risk on an individual basis, while macro risk management looks at statistical averages and aggregate samples. The power is in using the macro perspective to gain insight and knowledge about the whole while using the micro view to assess the individual risks for each project (Kendrick, 2003).

### **Existing Research**

As discussed in the following paragraphs, previous studies have explored the uncertainty associated with construction. The financial risk to both the owner and the contractor require that much care be taken before entering into such a venture. Unfortunately, this care often involves only a brief analysis based on the PM's experience of previous projects instead of a detailed evaluation and quantification of the proposed project's risk and uncertainty (Mustafa and Al-Bahar, 1991). Three relevant studies in the area of construction project related to risk identification and assessment will be discussed. These studies cover risk related to environmental remediation liability, the classification of a risk factor hierarchy related to construction in foreign countries, and a unique perspective related to the quantification of risk by using common language.

#### Environmental Remediation

The most relevant of these studies is by Jeljeli and Russell (1995), who quantified risk factors associated with environmental remediation projects. Using influence diagrams and decision trees, they used risk assessment to quantify the liability faced by a contractor bidding on a project. By surveying 80 companies involved in environmental remediation, they identified and rank ordered 53 risk factors based on respondents'

perceptions of importance. Table 2.1 shows the rankings from the survey. They concluded that 41 of these factors affect the likelihood of a liability claim. Five subject matter experts, who also provided the probability of each factor, validated the factors and their related influence. Figure 2.4 shows the interaction of these factors. Thus, Jeljeli and Russell (1995) produced a quantitative model capable of integrating “knowledge and experience acquired from multiple experts, project-specific knowledge, problem-solving and decision techniques” to estimate liability.

Table 2.1 Rank Order of Variables (Jeljeli and Russell, 1995)

<b>Risk Factor</b>	<b>Rank</b>	<b>Risk Factor</b>	<b>Rank</b>
Contract clauses	1	Reliability of technology	28
Private Owner indemnification	2	Constructability of design	29
Government indemnification	3	Demonstrated performance of technology	30
Type of project	4	Contractor past performance	31
Type of work	5	Source of contamination	32
Contract type	6	Pathways of contamination	33
Nature of contaminants	7	Owner management expertise	34
Potential third-party plaintiffs	8	Contractor reputation	35
Threat to nearby community	9	Partnering agreement	36
Contractor experience	10	Designer financial stability	37
Designer experience	11	Implementation of technology	38
Scope of engineering services	12	Owner reputation	39
Performance of technology	13	Designer reputation	40
Accuracy of design documents	14	Surety bonds	41
Insurance coverage	15	Designer past performance	42
Scope of construction	16	Time required to reach objectives	43
Effectiveness of technology	17	Useful life of technology	44
Potential contract party plaintiffs	18	Area of project site	45
Quality of design	19	Ease of start-up	46
Extent of contamination	20	Ease of installation	47
Designer management expertise	21	Time for implementation of technology	48
Owner financial stability	22	Cost of design effort	49
Contractor management expertise	23	Economy of design	50
Usability of design documents	24	Equipment requirements	51
Administrative and criminal penalties	25	Labor requirements	52
Threat to workers during construction	26	Material requirements	53
Contractor financial stability	27		

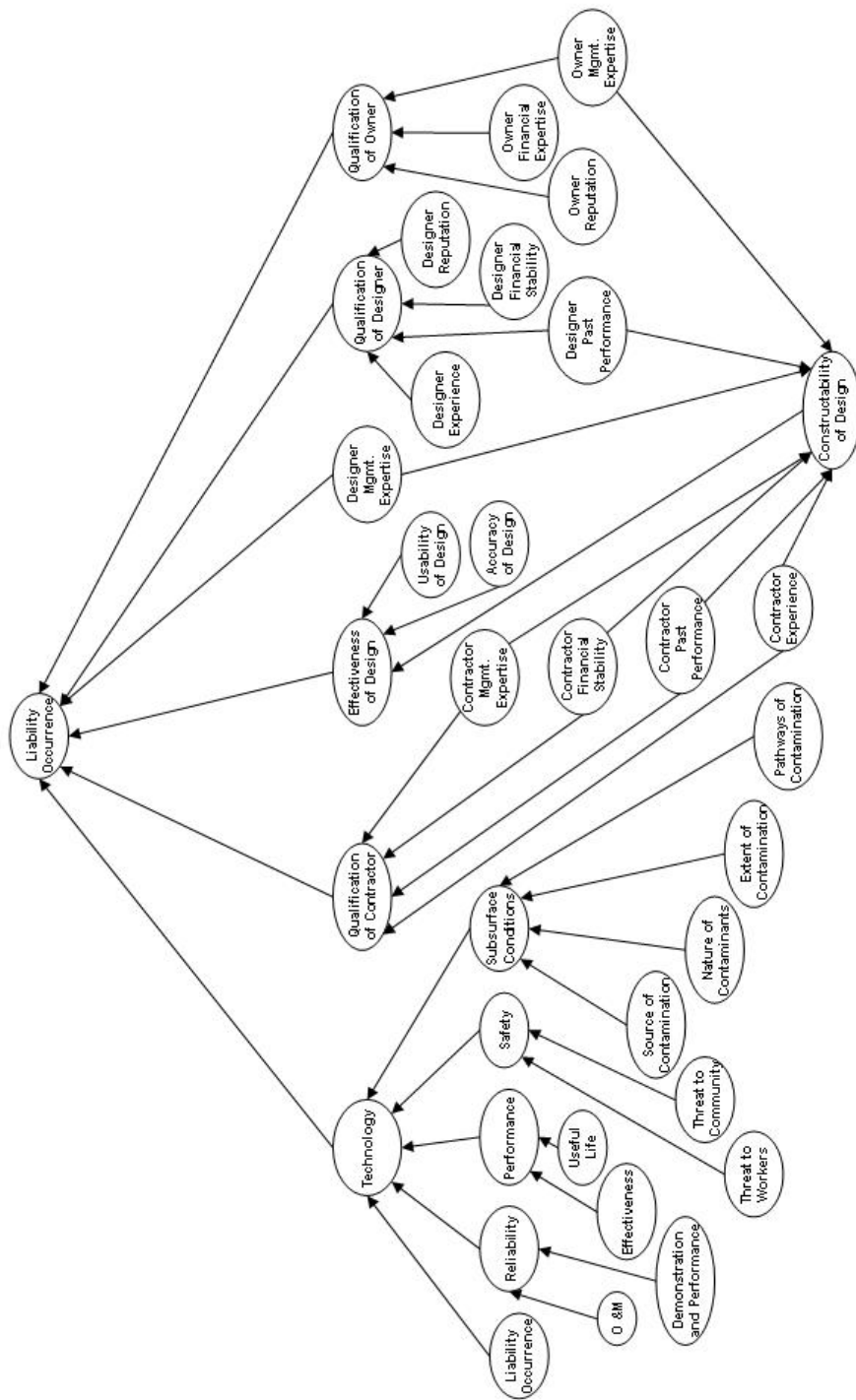


Figure 2.4 Influence Diagram (Jeljeli and Russell, 1995)

### Analytic Hierarchy

Mustafa and Al-Bahar (1991) assessed unanticipated risks related to construction projects and found a hierarchy of risk categories and factors similar to Jeljeli and Russell (1995). Mustafa and Al-Bahar (1991) contend that current models fall into one of two classifications: classical and conceptual. The classical is categorized by probability theory and analysis performed through influence diagrams and Monte Carlo simulations. On the other hand, the conceptual relies on subjective analysis such as the “fuzzy set analysis” performed by Kangari and Riggs (1989). Mustafa and Bahar (1991) utilized an Analytic Hierarchy Process (AHP) that involves “a multi-criteria decision analysis methodology that allows subjective as well as objective factors to be considered.” Figure 2.5 shows the hierarchical format of the risk factors developed by Mustafa and Al-Bahar (1991). Although there is no mention of how the risk factors were derived or developed, the categories established fall in line with previous research.

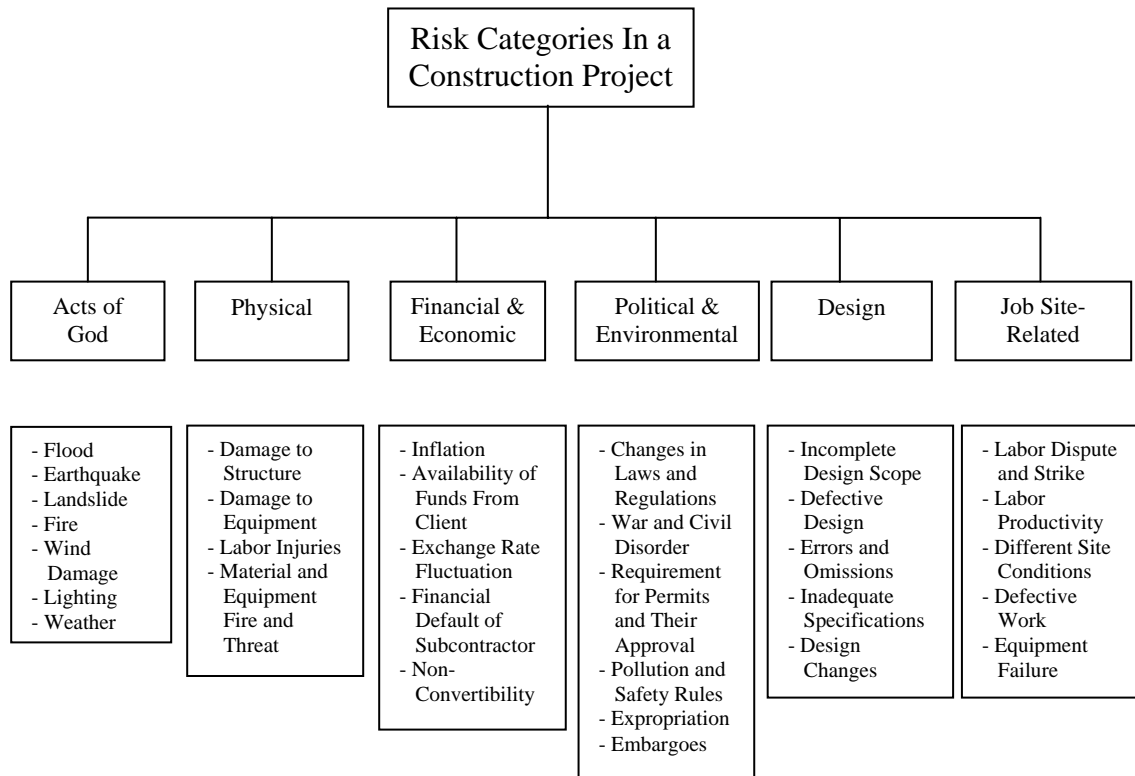


Figure 2.5 Hierarchy of Risk Factors (Mustafa and Al-Bahar, 1991)

### Linguistics

Kangari and Riggs (1989) present an innovative approach to quantifying risk.

Their approach is to utilize linguistic terms or words and to systematically assign a quantitative scale to represent those terms. For instance, an expert may classify risk as low, medium, or high. Kangari and Riggs (1989) extend that expert definition to a scale

of 1 to 10 in which the expert knows with 100% certainty that 1 is low, 5 is medium, and 10 is high. The uncertainty in the level of risk is represented by confidence intervals that include 2 through 4 and 6 through 9 as shown in Figure 2.6. These intervals represent an expert's confidence in classifying a variable as low, medium, or high. For example, a scale value of 4 can represent either a low risk with 10% confidence or a medium risk with 70% confidence. In this manner, Kangari and Riggs (1989) converted the subjective assessment of risk into an objective mathematical model.

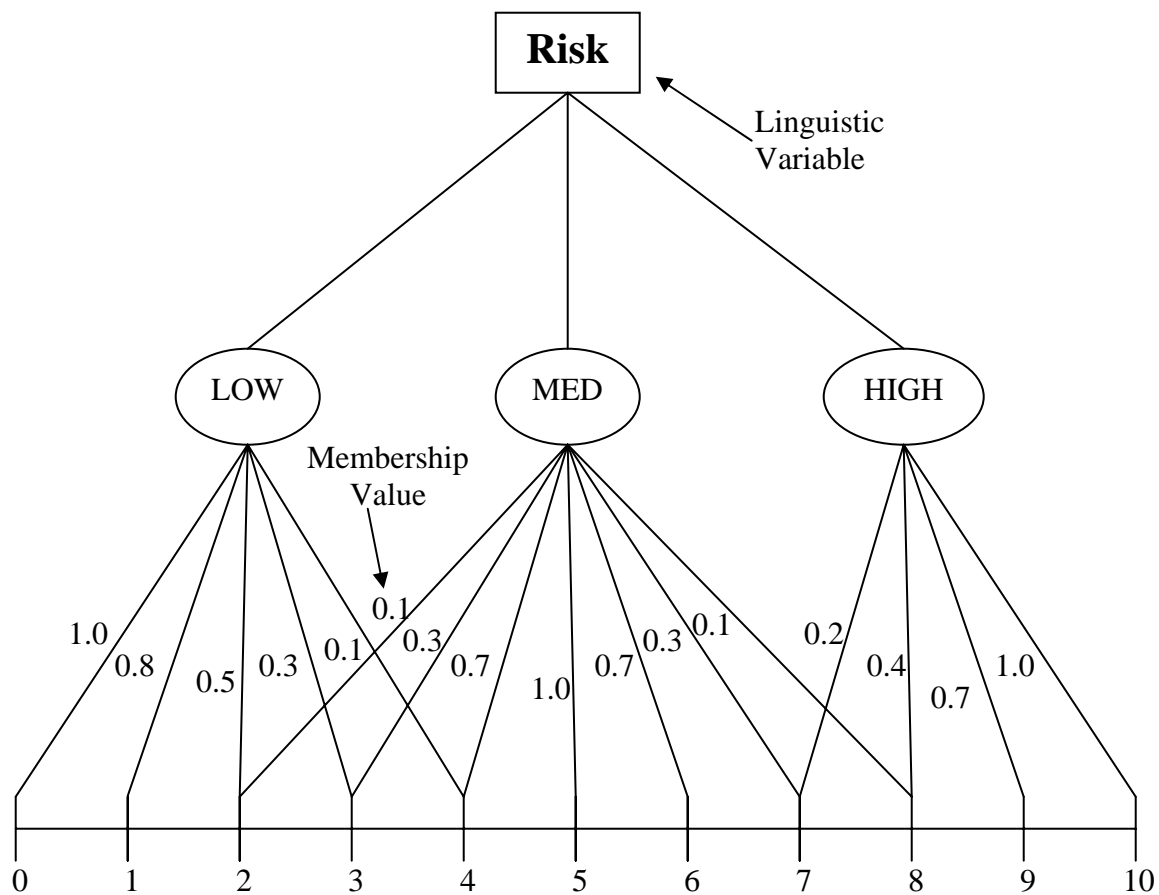


Figure 2.6 Confidence Interval Development (Kangari and Riggs, 1989)



## **Conclusion**

This chapter reviewed the applicable literature in the areas of construction management, earned value management, decision analysis, and risk. The content of this literature review will be used to form the foundation for the following chapter, which will explain the methodology used to construct the decision tree model. The model will attempt to quantify various aspects of construction management using decision analysis techniques to assess risk in an effort to determine if earned value management is applicable to construction projects.

## CHAPTER 3

### METHODOLOGY

The goal of this research was to develop a decision tool to enable decision-makers to make a “risk-based decision” to determine the applicability of an Earned Value Management System (EVMS) for fixed-price construction contracts within the Air Force. To meet this objective, the quantification of risk must be addressed and then the development of the possible risk scenarios must be explored. To address these risk issues, the Delphi method was initially used to gather and consolidate expert opinions. Decision Analysis (DA), specifically the application of a decision tree methodology, was used to evaluate the multiple variables of risk inherent in construction. Therefore, this chapter details the Delphi method and decision tree model used in this research.

#### **Delphi Method**

The Delphi method is a process by which objective data that is unavailable in quantitative form can be acquired through the use of multiple expert opinions to form a consensus (Clayton, 1997). It is an iterative process to acquire information from experts about a particular problem. To gain a better understanding of its applicability to this research, this section provides some fundamental background information related to the Delphi method.

## Historical Background

The name Delphi comes from mythology and references the predictive powers of the Greek necromancers at the oracle at Delphi (Gordon, 1994). The method developed from a project conducted in the 1950s by the RAND Corporation, which was hired to develop a list of targets in the United States that the Soviet Union would strike in the event of a nuclear attack (Linstone and Turoff, 1975). Gordon credits the beginnings of Delphi to the RAND efforts: “Olaf Helmer, Nicholas Rescher, Norman Dalkey, and others at RAND developed the Delphi method, which was designed to remove conference room impediments to a true expert consensus.” Rather than rely on subjective data or a single expert, the concept was to gain consensus among experts as to which sites were most likely to be targeted. Known as “Project Delphi,” the RAND study became the basis for the Delphi method (DeReus, 2004).

## Basic Process

The process encompasses a systematic approach to accomplish the objective of gaining expert opinion to acquire quantitative data. Building on the original three steps, other research has modified the process. Several methods will be discussed; the strengths and weaknesses identified, and the steps will be explained.

The original process consisted of a three step approach. Gunaydin (1999) identifies the basic elements of the original process as “(1) structuring of information flow, (2) feedback to the participants, and (3) anonymity for the participants.” The process provides a better flow of communications while eliminating the pitfalls of group dynamics to maintain focus on the issue (Jensen, 1981).

An evolution of the three-step process is the five-step approach presented by DeReus (2004) and shown in Figure 3.1. Summarized from information provided by Ryerson University, DeReus (2004) offers the following explanations of process steps. Step one is simply the identification of the problem, which reinforces the need to understand the problem before proceeding. Step two requires the identification and selection of experts. The intent is to elicit input from individuals knowledgeable and experienced in the field related to the problem. This continues the focus on the problem identified in step one. Having identified the Subject Matter Experts (SMEs), Steps three and four are a repeating loop. Steps three and four entail the fundamentals of steps two and three identified by Gunaydin (1999) in the original process. By performing repetitive iterations, the process ensures participants gain feedback for each loop. Steps three and four are iterative processes that repeat in order to reach consensus by the SMEs concerning the identified problem. Step five translates the data gained through the Delphi Method (DeReus, 2004).

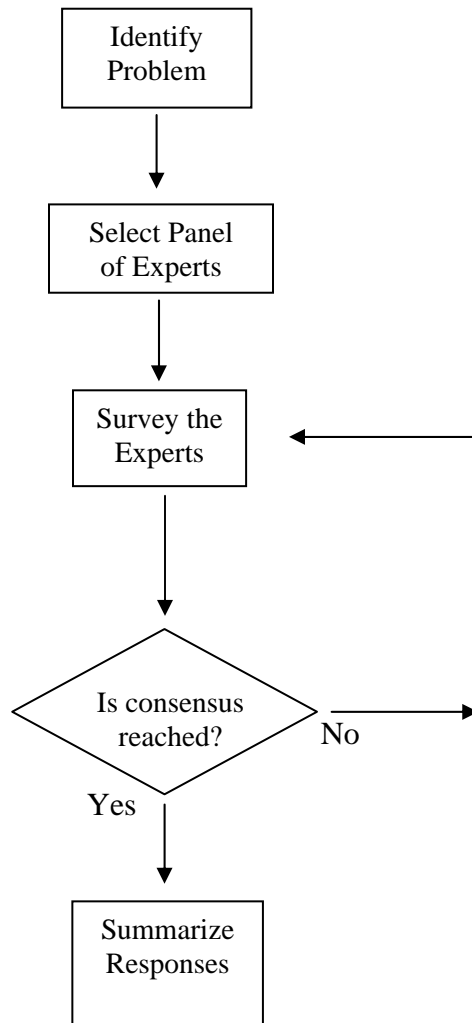


Figure 3.1 Basic Process (DeReus, 2004)

As an expansion on the original three-step process and to further refine the process, Fowles (1978) offers the following process steps:

1. Formation of a team to undertake and monitor a Delphi on a given subject.
2. Selection of one or more panels to participate in the exercise. Customarily, the panelists are experts in the area to be investigated.
3. Development of the first round Delphi questionnaire
4. Testing the questionnaire for proper wording (e.g., ambiguities, vagueness)
5. Transmission of the first questionnaires to the panelists
6. Analysis of the first round responses
7. Preparation of the second round questionnaires (and possible testing)
8. Transmission of the second round questionnaires to the panelists
9. Analysis of the second round responses (Steps 7 to 9 are reiterated as long as desired or necessary to achieve stability in the results.)
10. Preparation of a report by the analysis team to present the conclusions of the exercise

Although similar to the basic process, Fowles' (1978) process provides additional detail and refinement to improve the effectiveness of the method. The key element added by Fowles (1978) is that of testing. He proposes testing of the first round questionnaire and possible testing of questionnaires in subsequent rounds before proceeding.

### General Areas of Application

The areas in which the Delphi method has been used vary greatly. From its initial use as a prediction tool, it has developed into a tool that has broad applicability across many disciplines. Linstone and Turoff (1975) contend that it is used “in the field of planning, Normative Forecasting, Planning Programming Budgeting Systems (PPBS), and Cost-Effectiveness or Cost-Benefit Analyses.” In his examination of Delphi, DeReus (2004) presents its extensive use in engineering and the physical sciences as well as economics and business. The benefit of Delphi is its effectiveness when data is too costly or time inhibitive to collect (DeReus, 2004)

### Strengths

The basic premise of Delphi is consistent regardless of the exact approach that is used: expert opinion and consensus is more accurate and more reliable than that of a single individual. The ability to construct dependable data from subjective responses to reach quantifiable results demonstrates the power of the Delphi method (Gunaydin, 1999). The method’s primary strength is its ability to draw on and form a consensus of experts without requiring those experts to come together and meet. The lack of excessive cost and planning typically associated with bringing individuals together are other strengths of the Delphi method (DeReus, 2004). Mattingley-Scott (2006) offers these benefits regarding the method: “rapid consensus, participants can reside anywhere in the world, coverage of [a] wide range of expertise, [it] avoids groupthink, [and its ability of] forecasting a specific, single-dimension question.” A further benefit is the iterative nature of the process which ultimately forms the benefit of consensus (DeReus, 2004).

In addition, the process is flexible enough to enable variations in the investigative portion. Gordon (1994) contends that although the initial and final steps may be similar in different processes, the questionnaire phase can vary greatly. In fact, Gordon (1994) offers three distinct methods that can be used to question the SMEs. One method is to simply use the first round data in quantitative decision models. The subsequent analysis of the model validates the expert opinion and determines if the differences in the expert opinions are statistically significant. The second method is one-on-one interviews in which the interactive nature allows for more flexibility than with a questionnaire. In addition, interviews can be directed based on interviews with previous experts, which Gordon (1994) calls “Feed-Forward.” Although interviews are therefore different, the objective is reached. Finally, Gordon (1994) offers group meetings as the third method. This conflicts with the original premise of anonymity, but it is acceptable in situations where the topic of discussion is not sensitive or controversial and will not elicit strong responses which may drive the focus of the group (Gordon, 1994).

The Delphi method offers many benefits to the researcher, some of which were mentioned above. Its ability to leverage multiple expert opinions while eliminating the expense to bring those individuals together, its iterations to form consensus, and its flexibility make it an excellent tool. However, no method is without criticism and those ideas will be expressed in the next section.

### Weaknesses

The criticisms of Delphi fall into three main categories: selection of the experts, bias imposed by the research, and reliability. Clayton (1997) contends that expertise is



not a measurable quantity; therefore, the selection of experts is a very subjective process. Furthermore, an individual's knowledge and experience related to a particular subject does not necessarily correlate to the quality of the input provided; additionally, experience may prevent alternatives outside of the normal paradigms related to that subject (Mattingley-Scott, 2006).

The second criticism relates to the researcher. DeReus (2004) points out that the opportunity for bias exists through the researcher's examination, summation, and formulation of each round of responses and questions. In addition, the simplistic nature of the Delphi method can create a false sense of ease and diminish the critical nature needed in the refinement of each round of questions and responses (Clayton, 1997).

The third criticism is the reliability of the process itself. Although this relates back to the selection of the experts, the question is whether the data is reproducible with similar experts responding to the same questionnaires (DeReus, 2004). In addition, the issue of reliability permeates into the depth of investigation concerning differences in responses between rounds (Mattingley-Scott, 2006). The result of the criticism is that with any method, care must be taken to ensure the scientific method is followed and to understand that all results are subject to interpretation and discussion.

## **Decision Tree**

A decision tree is designed to show decisions, risk, cost, and probabilities in a graphical representation. As the name implies, the tree represents the flow of the relationship between choices available to a decision maker and the possible outcomes of chance events which are out of the decision maker's control (Haimes, 2004). This

research relied on two methods to construct the decision tree. The first method used DPL 4.0 (decision analysis software) and failed due to excessive computational time requirements; therefore, Microsoft Excel Visual Basic was used. After a general discussion of the strengths and weaknesses associated with the use of decision trees, both methods will be explained in more detail.

### General Strengths and Weaknesses

Decision trees have several strengths and weaknesses. The primary strengths are that it can handle multiple types of input, can be validated with statistical methods, and can handle large amounts of data quickly (Weir, 2005). The weaknesses range from the complexity, which can quickly escalate, to the graphical nature of the diagram.

Complexity can quickly become a problem because of the exponential growth of the tree when additional chance events are added. This also leads to a cumbersome graphical representation that is neither easily viewed nor comprehended. The individual strengths and weaknesses of DPL and Microsoft Excel Visual Basic will also be discussed in the following sections.

### DPL

DPL is a computer program developed by Applied Decision Analysis LLC for modeling influence diagrams and decision trees (Borison et al., 1998). In addition, the program offers the advantage of being able to convert influence diagrams into decision trees. This gives the modeler the capability to graphical represent a decision through the

use of an influence diagram, which is relatively simple. The program will automatically convert the relationships described in the influence diagram into a decision tree.

DPL also provides the capability to conduct sensitivity analysis. Several processes are available to help the decision maker understand the range of values and their impact. The first is a tornado diagram, which indicates the range over which the variables can change and the impact of those changes on a particular decision. A variable with a greater the range is shown by a longer bar on the tornado diagram. The color of the bar for a given variable may change as well; this demonstrates where the choice of alternatives would change if the variable changed to that extent. For example, the decision to produce a product to sell will depend on factors such as market size, the companies' share of that market, selling price, fixed costs, and variable costs. An analysis of these risk factors will reveal that share of the market fluctuates to a greater extent than variable price. Therefore, market share should be examined and tracked more than the variable price to manage the risk from producing the specified product. The tornado diagram of this example is shown in Figure 3.2.

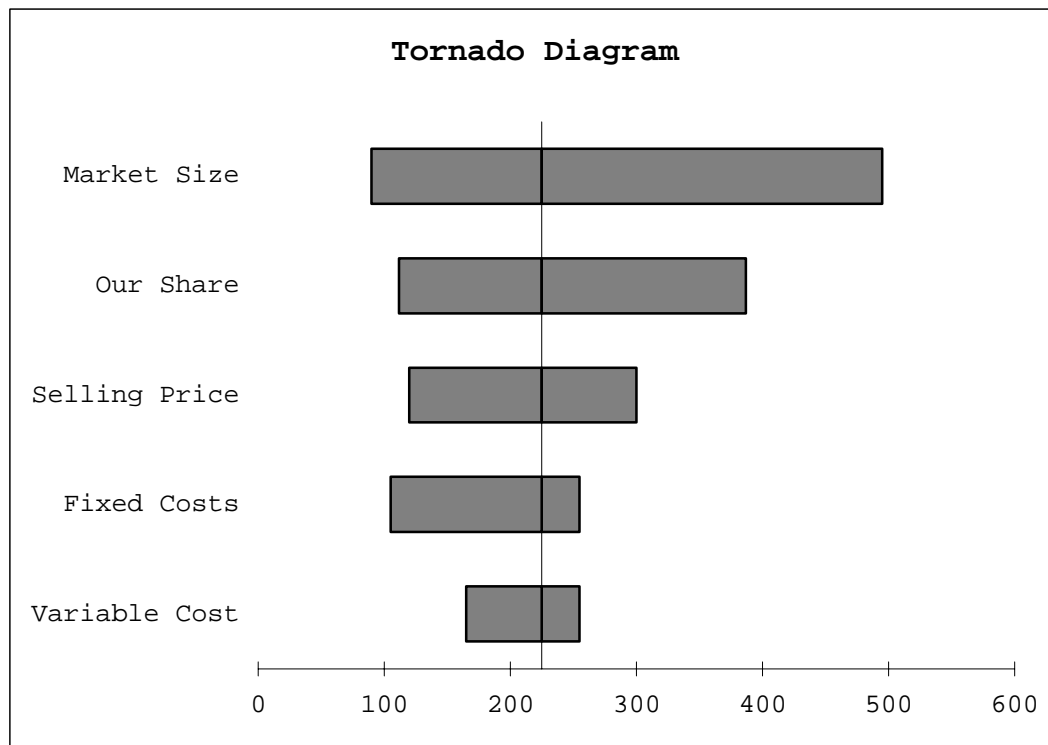


Figure 3.2 Tornado Diagram (Borison et al., 1998)

Another feature of DPL is the risk profile. As Borison et al. (1998) put it, “risk profiles graphs the range of outcomes under alternative strategies [and] help understand which strategies offer the most risk and which offer the most potential.” As in the previous product example, decisions affect the risk factors and the probability of an outcome from that decision is demonstrated by the risk profile. An example of a risk profile is shown in Figure 3.3.

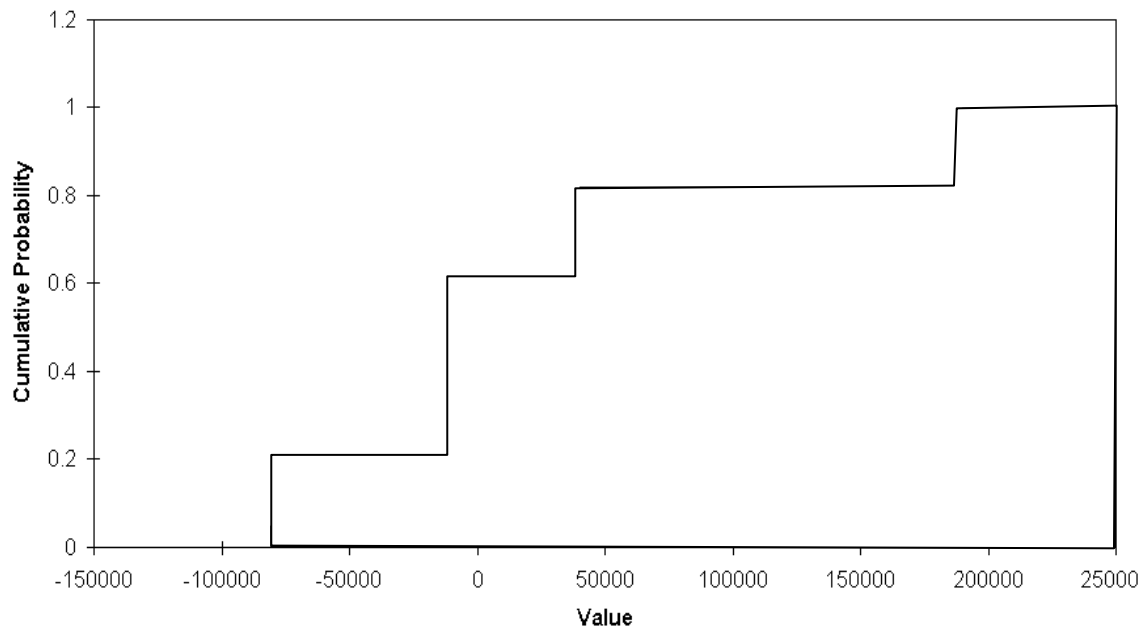


Figure 3.3 Risk Profile (Borison et al., 1998)

Unfortunately, DPL is limited by the number of chance events it can evaluate. In a test of the program using 13 risk variables with a range of three possible scenarios, the computer program failed to produce an output. Subsequent runs with fewer variables produced the same result. For this reason, DPL could not be used for this research.

### Microsoft Excel

Using Microsoft Excel and Visual Basic Editor, a computer program can be written which will evaluate and calculate the risk scenarios demonstrated in a decision tree model. Although Microsoft Excel allows for the computation of the nearly two million scenarios likely in this research, the program has its limitations. The program does not have a preset sensitivity analysis capability similar to that available through DPL 4.0 software. The tornado diagram that provides insight into the range of the risk factors is not available; however, subroutines can be written to track the information needed to graph the probability distribution and cumulative probability. Examples of each are shown in Figures 3.4 and 3.5. Although the lack of a sensitivity analysis feature is a limiting factor, the capability of Microsoft Excel to compute the full range of risk scenarios makes it superior to DPL 4.0. Thus, the Microsoft Excel decision tree model provides the basis for this research.

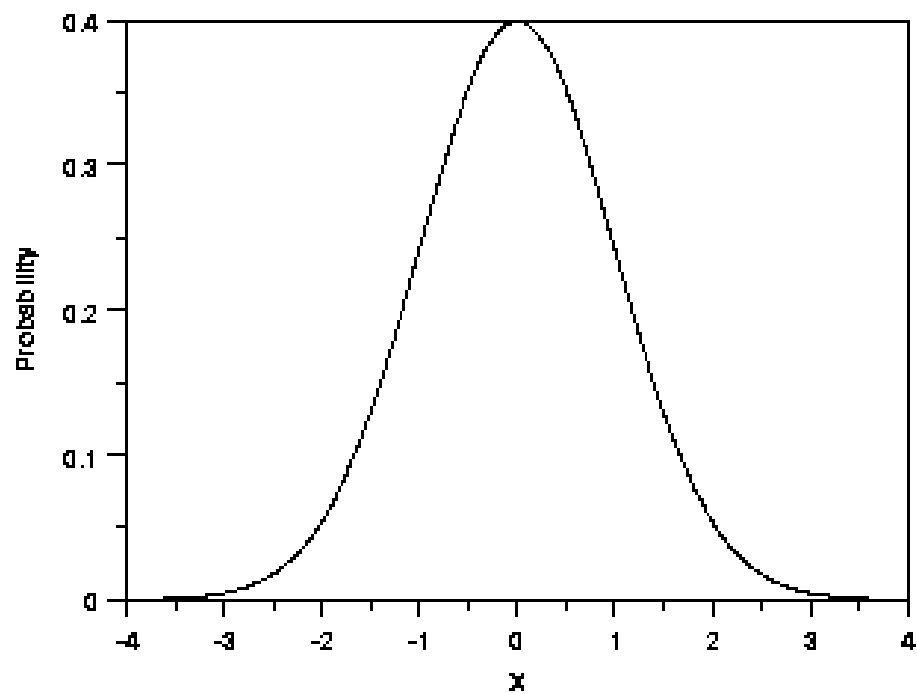


Figure 3.4 Probability Distribution (*NIST/SEMATECH*, 2006)

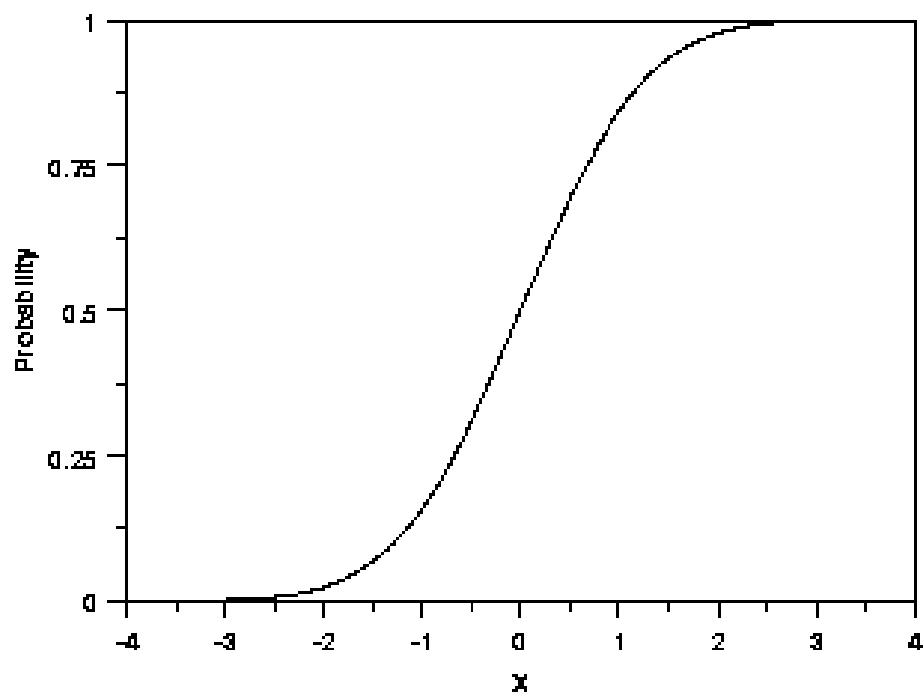


Figure 3.4 Cumulative Probability (*NIST/SEMATECH*, 2006)

## **Conclusion**

The methodology used in this research attempts to quantify the risk associated with construction. The risk factors were gleaned from relevant literature, confirmed and expanded for likelihood and impact through the Delphi method with Subject Matter Experts. Using the data acquired, a decision tree model was developed using DPL and subsequently in Microsoft Excel. The purpose is to develop a model, which will assist a decision maker in determining the applicability of EVM for construction. The success of this effort and the further exploration and analysis of the model will be discussed in the next chapter.



## CHAPTER 4

### RESULTS AND DISCUSSION

This chapter presents the results of applying the methodology explained in Chapter 3. After first describing how the appropriate data was collected, the chapter discusses the formulation of the model developed in this research. It also explains how the model was adapted in response to inputs from Subject Matter Expert (SME) opinion. The overall result is the development of a decision tool that will help Air Force (AF) personnel manage construction projects. The tool helps project managers (PMs) identify the risks associated with a project and determine whether that risk warrants the use of earned value management (EVM). The model is based on a decision tree which uses either the aggregate assessment of opinions from SMEs or the PM's specific knowledge of the project to predict expected cost growth. The decision-maker then has the choice of using EVM during the project to anticipate problems and help mitigate risk.

#### **Data Collection Efforts**

The data for this research effort was collected through the use of the Delphi method. As discussed in Chapter 3, the Delphi method utilizes an iterative process. The results from applying each of these steps are expressed in the following sections. The Delphi method was appropriate for this research; it attempted to garner expert opinion from multiple sources as a way to determine an aggregate assessment of the current risks experienced by PMs in the construction field.

### Step One

The first step in the Delphi method is to assess the problem. The problem arises from the revised policy that requires a “risk-based decision” to determine whether EVM should be used for projects valued at less than \$20 million. Since most military construction (MILCON) projects fall into this category, this revised policy is applicable PMs in the civil engineering organization. Therefore, the problem to be assessed in this step is to identify the risks associated with AF construction projects.

The problem arises from a need to perform a risk-based decision to determine whether sufficient cost or schedule risk exists to necessitate EVM for firm-fixed price construction contracts. Cost and schedule risk create the cost growth associated with AF construction projects. The relevant cost growth data is provided in the Automated Civil Engineering System (ACES). The information, however, is incomplete and difficult to extract. Therefore, the Delphi method was chosen to overcome this lack of quantifiable cost growth data and focus on the quantification of the associated risk factors, which are inherently subjective rather than objective.

### Step Two

Step two of the Delphi method is to identify appropriate experts. For this research, this meant finding experts associated with management of construction projects in the AF. The choice was to consult members of the Air Force Center for Environmental Excellence (AFCEE) at Brooks City Base in San Antonio, Texas. Five AFCEE project managers were selected based on their first hand knowledge of construction and their contract management experience in project modifications and

change orders. These individuals represent years of construction management experience from which to draw professional expertise. Their recent project management experience includes \$1.2 billion in construction in 2002, over \$1.2 billion in Iraq reconstruction in 2004, projections of \$2 to \$2.5 billion in 2005 and 2006 for Iraq reconstruction, and most recently the rebuilding effort at Keesler Air Force Base, Mississippi, following the devastation due to Hurricane Katrina (AFCEE Website, 2006). To ensure the anonymity of these SMEs, they will be referred to only by a letter designation.

### Step Three

Step three is the repetitive loop of querying the SME and consolidating the results to form a consensus; it was conducted in three phases. The first phase reviewed the relevant literature to develop applicable construction risk factors. The second phase asked the SMEs to validate the relevant risk factors related to AF construction projects, while the third phase determined the likelihood and impact of the identified risk factors. The three phases were conducted in an iterative process and are described in the following paragraphs.

Phase One: The literature review included previous research that had identified risk factors for specific types of construction. For example, Mustafa and Al-Bahar (1991) used the Analytic Hierarchy Process (AHP) to quantify the risks associated with construction projects in foreign countries. They established the six categories and 32 factors previously shown in Figure 2.5. As a reminder, the categories were Acts of God, Physical, Financial and Economic, Political and Environmental, Design, and Job Site-Related. Since the current research effort is focused on projects in the United States in

the public sector, the Financial and Economic along with the Political and Environmental factors were not applicable. Of the remaining 24 risk factors, the ones used in this research were weather, differing site conditions, design accuracy, and design changes. By expanding their definitions, these four accurately encompassed the remaining 20 and were, therefore, not listed independently. The four were applicable and relevant to Air Force construction efforts and would produce cost growth if they were not controlled.

Jeljeli and Russell (1995) used industry surveys and SMEs to establish 41 critical risk factors and probabilities, which were rolled up into the six broad categories of Risk of Technology, Qualification of the Contractor, Effectiveness of Design, Designer Management Expertise, Qualification of Designer, and Qualification of the Owner. Their study identified risk factors related to environmental projects, which are closely related to building construction. This research attempted to use similar techniques to estimate the construction cost growth or required contingency amount based on risk. Similar risk categories are involved, with two primary differences. Since technology was specifically related to remediation techniques and sub-surface contamination, the respective factors were not applicable. Qualifications of the owner are unique with respect to this research as the owner is considered to be the AF; thus, aspects of reputation and financial stability were not considered. After discounting technology and owner qualifications, 4 categories with 15 factors remained. The factors considered due to their influence on construction cost growth included contractor experience, contractor past performance, contractor management expertise, constructability of design, designer experience, and designer past performance; the category of Designer Management Expertise (which did not include

factors) was also considered relevant. Accuracy of design was also applicable but was identical to a factor used from Mustafa and Al-Bahar (1991).

This research also included additional factors for the SME to consider based on inputs they provided. Drawing on the research applicable to new construction and renovation projects, four factors from Mustafa and Al-Bahar (1991) and seven factors from Jeljeli and Russell (1995) established the 11 initial risk factors. In addition, four other factors were presented to the SMEs for consideration: age of facility, asbestos, duration, and proximity of designer to site. Age and asbestos were added as specific indicators related to the conditions of existing facilities to be renovated. Duration and proximity were added as possible influences. Together, these 15 factors were a first step in the problem of quantifying risk. These factors, and the four categories within which they fall, are shown in Table 4.1. These risk factors established the starting point from which to proceed to phase three.

Table 4.1 Initial Risk Factors

<b>Factors</b>	<b>Sub-Factors</b>
Physical	Age of Facility
	Weather
	Asbestos
	Sub-Surface
Contractor	Experience
	Past Performance
	Management Experience
Design	Accuracy
	Constructability
	Duration
	Changes
Designer	Experience
	Past Performance
	Management Expertise
	Proximity

Phase Two: Through the literature review conducted in this research, a composite list of 15 risk factors was developed. The individuals, although co-located, were queried separately and asked to provide individual responses. Querying those individuals separately avoids the possibility of “Group Think” which is the tendency of one or more dominant personalities to override and sway consensus to their views (Clayton, 1997). The SMEs were asked to give their opinion on the relevance and applicability of the listed risk factors based on their knowledge of and experience with AF construction projects. In addition, the SMEs were given the opportunity to add to the list of risk

factors if they felt the list was not complete. The SMEs initially added four risk factors to the list (see the “Interim List” column in Table 4.2). After several iterations in which the definitions and descriptions of the factors were further refined, the final list was comprised of the 13 factors shown in the “Final List” column of the table.

Table 4.2 Risk Factor Development

<u>Initial List</u>	<u>Interim List</u>	<u>Final List</u>
1. Age of Facility	1. Age of Facility	1. Age of Facility
2. Weather	2. Weather	2. Weather
3. Asbestos	3. Asbestos	3. Asbestos
4. Sub-Surface (Ground and interior for renovation)	4. Sub-Surface (Ground and interior for renovation)	4. Sub-Surface (Ground and interior for renovation or Differing/unforeseen site conditions)
5. Contractor Experience	5. Contractor Experience	
6. Contractor Past Performance	6. Contractor Past Performance	
7. Contractor Management Experience	7. Contractor Management Experience	5. Contractor Experience
8. Designer Experience	8. Designer Experience	6. Contractor Past Performance
9. Designer Past Performance	9. Designer Past Performance	7. Contractor Management Experience
10. Proximity of Designer to construction location	10. Proximity of Designer to construction location	
11. Designer Management Expertise	11. Designer Management Expertise	8. Designer Experience
12. Design Accuracy	12. Design Accuracy	9. Designer Past Performance
13. Design Constructability	13. Design Constructability	10. Design Accuracy
14. Project Duration	14. Project Duration	11. Design Constructability
15. Opportunity for Design Changes	15. Opportunity for Design Changes	12. Project Duration
	16. Type of Facility to be constructed	13. Opportunity for Design Changes
	17. Users understanding of design before construction	
	18. Differing/unforeseen site conditions	
	19. Changes in user requirements	



Phase Three: The third phase was the development of the likelihood of occurrence and impact of each of the final risk factors. The SMEs were asked to consider 100 projects and, using their knowledge and experience, categorize each risk factor into three levels of risk. The definition for each risk factor varied but was briefly categorized for the SME. For example, weather was defined as being mild, normal, and severe. The definitions provided to the SMEs are shown in the range column of the table in Appendix C. The concept was for the SMEs to identify the number of projects out of 100 associated with each level of risk for each risk factor. For instance, consider Contractor Past Performance. The SME may have thought that 30 projects had low or poor Contractor Past Performance, 60 experienced a normal level of performance, and 10 had contractors with exceptional or high past performance. Phase two also asked the SMEs to rate the cost impact of experiencing the specified level of risk for each factor using a standard project cost of \$1 million. Continuing with the Contractor Past Performance factor, the SME may have thought that a contractor with poor past performance might cost the government an additional \$100,000, which would equate to a 10% cost growth. Additionally, a contractor with normal past performance might experience a \$50,000 cost growth, while the exceptional performer would encounter zero cost growth. The limiting factor of this step was that only three of the five SMEs responded.

#### Step Four

Step four is the consolidation and summary of the responses acquired from the previous Delphi method steps. The data developed from the Delphi method is provided in Appendix C. The first column lists the risk factors developed in step three from the

five SMEs. Column two contains descriptions of the risk levels, with column three providing a definition in the range column. The next six columns represent the probability and cost impact provided by the three SMEs. The data shown the last three columns was consolidated through statistical averaging to formulate a consensus of the SMEs estimates for Risk Factor likelihood and cost impact. Appendix D represents step four of the Delphi process and thus the end of this portion of the research.

### Conclusion of the Delphi Method

With the Delphi portion of the research complete, the data acquired will be used to construct a predictive decision model. The model will be built using the decision tree method in an effort to expand each risk factor through each level of risk to determine an expected value. The expected value returned by a decision tree model will be the expected cost growth for a project. Therefore, it will be representative of the amount of contingency funds required cover unforeseen events associated with a construction project.

### **Decision Tree**

The decision tree model is formulated through a progressive expansion of each risk factor and its risk levels. The expected value is determined through a process of rolling back each branch in the tree (Jensen, 2001). For an AF construction project, a decision tree would yield a dollar value representing cost growth based on the probability distribution of the risks. The result is a distribution of the expected cost growth and the associated probability of that outcome. The expected value result is a quantification of

the cost growth that the decision maker can use to decide whether or not to use EVM. Using the 13 risk factors and their three levels of risk developed through the Delphi method, the resulting decision tree model has a final expansion of 1,594,323 branches. The development of the model was initially constructed using DPL 4.0, which is a professional decision analysis software. However, the computing time using this software was prohibitive. Therefore, the model was reconstructed by programming a routine in Microsoft Excel using Visual Basic Editor. Each process will be explained in order to discuss the results of the model.

#### DPL 4.0

DPL 4.0 was initially selected because of its ability to convert influence diagrams into decision trees. The graphical nature shows the relationship between a decision and the multitude of influences reflected in the decision. Therefore, the influence diagram shows what factors effect the cost growth of a project. The amount of cost growth helps the decision maker determine the applicability of EVM. The initial iteration of the model is shown as an influence diagram in Figure 4.1. The subsequent decision tree model is shown in an abbreviated method (i.e., not fully expanded) in Figure 4.2. Due to the size of the decision tree, the model execution was incomplete after 72 hours of computing time. The failure seemed to be the result of insufficient computing power and memory capacity of DPL to handle a decision tree of this size: 13 risk factors evaluated at three risk-levels resulting in almost 1.6 million branches or possible outcomes. As a result, another method for developing and solving the model had to be found.

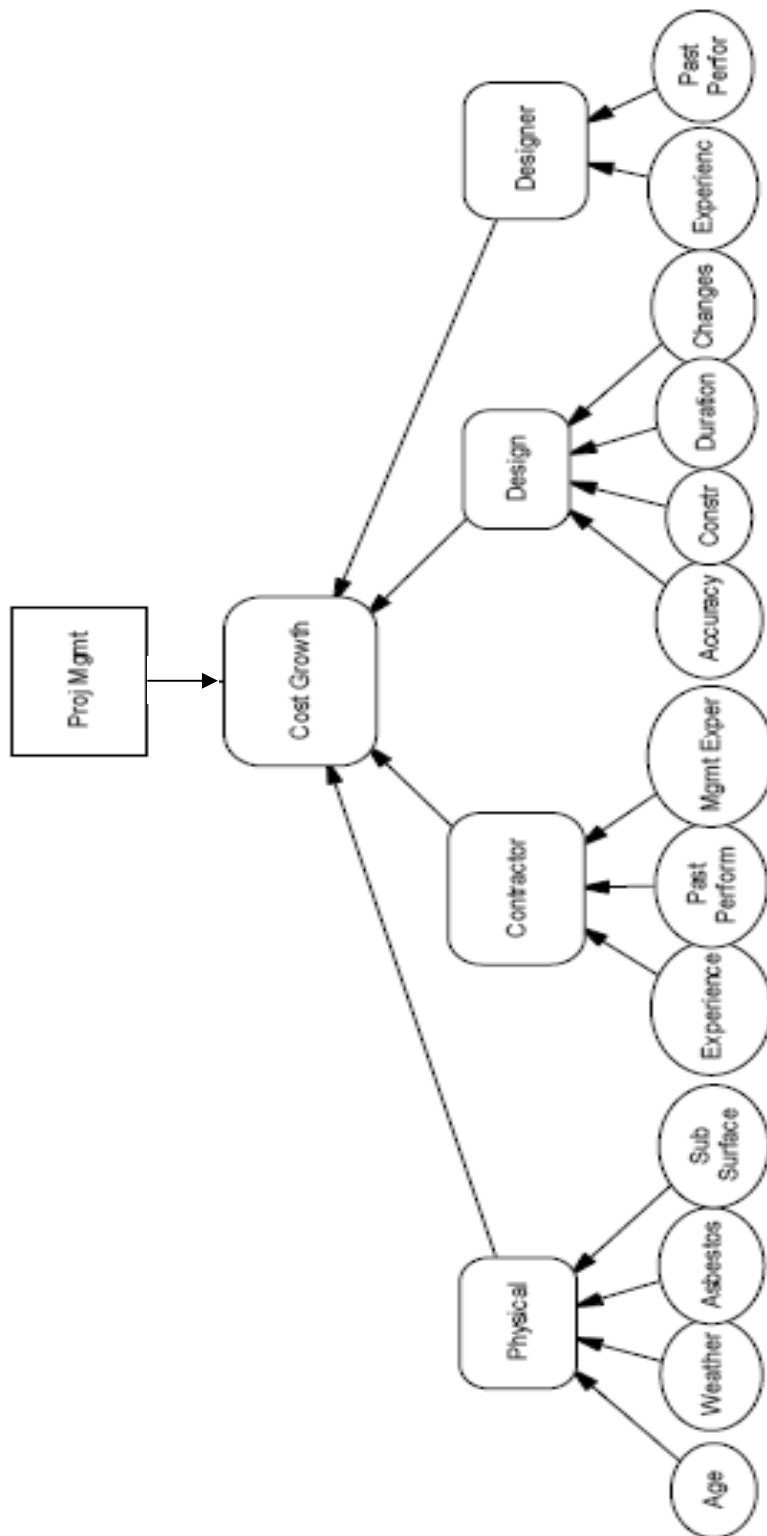


Figure 4.1 DPL Initial Influence Diagram

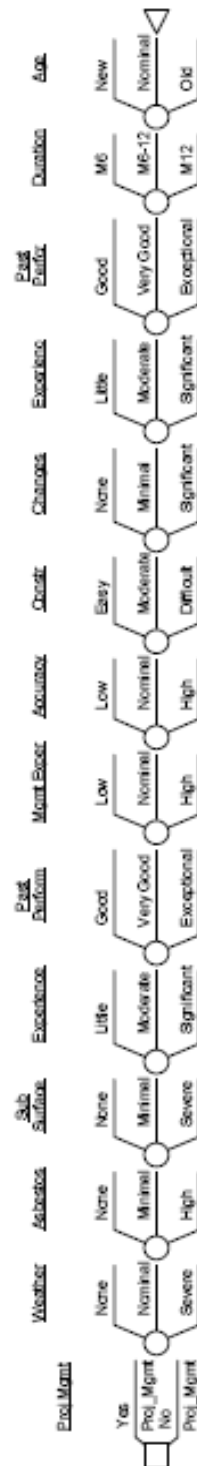


Figure 4.2 DPL Initial Decision Tree-Unexpanded

### Microsoft Excel Visual Basic

The next iteration of the model was programmed in Microsoft Excel using the Visual Basic Editor. Using this programming language, the 13 risk factors were assigned a two-dimensional value to capture the likelihood of occurrence and the cost impact associated with each level. The process to explore the nearly 1.6 million possible outcomes was accomplished through a series of imbedded loops. Each loop is repeated for each risk factor and again for each risk level. The calculation of the expected value was performed through a progressive summation of each of the 1.6 million iterations. The entire program is shown in Appendix D. The input data for the program is gathered with a template using an Excel spreadsheet, as shown in Figure 4.3.

To test both the spreadsheet and the model, the collective input from the SMEs was used. Based on a project estimate of \$10 million, the results of the initial run of the decision tree resulted in an expected cost growth of \$5,958,851.22, which represents a 59.6% cost growth (discussion is covered in the analysis section). The distribution of the 4772 distinct outcomes is shown graphically in Figure 4.4. In addition to the distribution of the possible outcomes and their associated probabilities, the model also outputs the cumulative probability of the possible outcomes. This is shown in Figure 4.5.

Risk-Based Decision Model										
Original Cost Estimate = \$ 10,000,000										
Age			Weather			Asbestos			Probability % Cost Growth	
New	Nominal	Old	None	Nominal	Severe	None	Minimal	High		
0.6166	0.1667	0.2167	0.2333	0.5	0.2667	0.35	0.35	0.3		
0.00500	0.04500	0.16667	0.00000	0.02000	0.06333	0.00500	0.05667	0.12667		
Sub-Surface			Contractor Experience			Contr Past Performance			Probability % Cost Growth	
None	Minimal	High	Little	Moderate	Significant	Good	Very Good	Exceptional		
0.5	0.2833	0.2167	0.1667	0.5333	0.3	0.2167	0.6333	0.15		
0.01167	0.05667	0.13333	0.04667	0.01633	0.00000	0.09333	0.03000	0.00000		
Contr Management Experience			Design Accuracy			Constructability			Probability % Cost Growth	
Low	Nominal	High	Low	Nominal	High	Easy	Moderate	Difficult		
0.1833	0.5667	0.25	0.5333	0.35	0.1167	0.2833	0.5167	0.2		
0.07500	0.02833	0.00000	0.15000	0.02833	0.00000	0.00000	0.02000	0.08667		
Duration			Changes			Designer Experience			Probability % Cost Growth	
<8M	8-18M	>18M	None	Minimal	Significant	Little	Moderate	Significant		
0.1333	0.4167	0.45	0.1667	0.5	0.3333	0.1833	0.6	0.2167		
0.01167	0.03167	0.06833	0.04667	0.07167	0.10667	0.12000	0.01833	0.00000		
Designer Past Performance										Probability % Cost Growth
Good	Very Good	Exceptional								
0.25	0.6	0.15								
0.11667	0.03667	0.00000								

Figure 4.3 Risk Factor Input Sheet

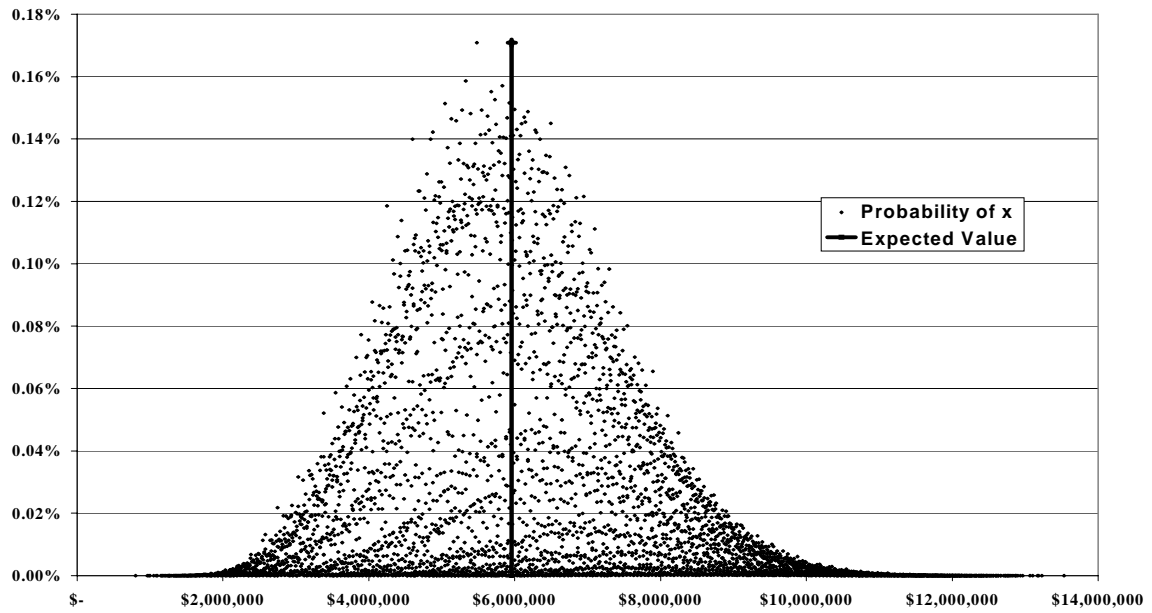


Figure 4.4 Initial Model Results – Probability Distribution



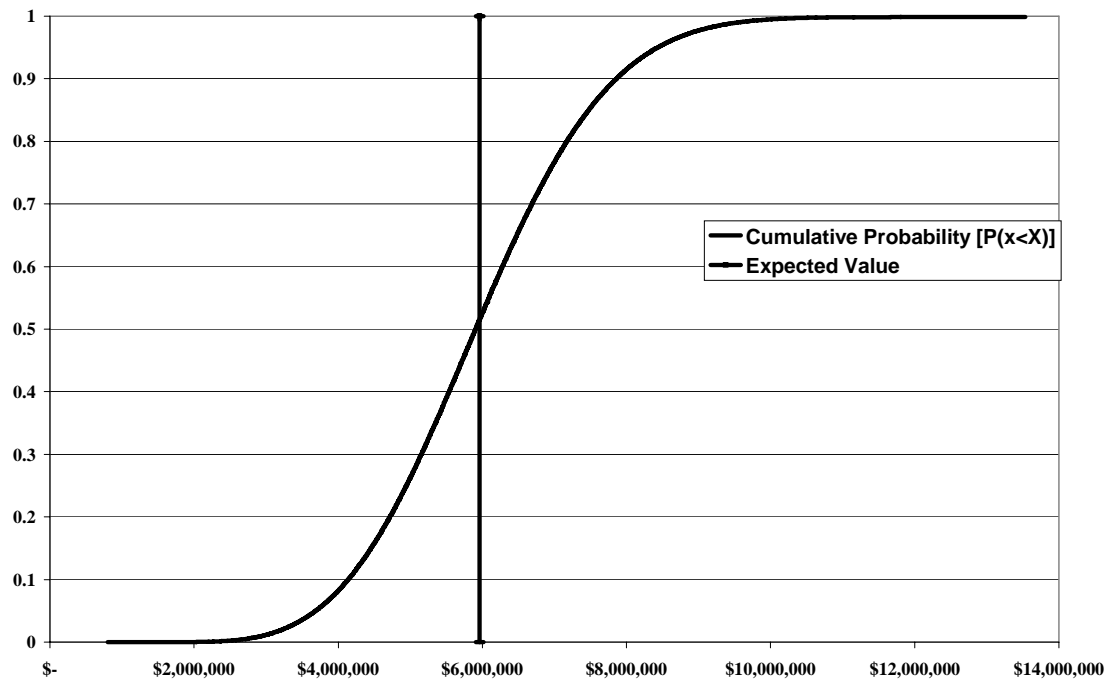


Figure 4.5 Initial Model Results – Cumulative Probability

## Analysis

With the model formulated and running, the results of the output must then be examined. This analysis will be conducted in two phases. The first phase will look at the results of the initial model and the nature of the cost growth. The second phase will attempt to refine the model and produce an interactive version that can be used by a project manager to assess his/her specific project.

## Phase One

The results of the initial model's output predicted a cost growth of nearly 60%. To understand the nature and size of this result, the individual data from each SME was loaded independently into the model. The SME's data returned cost growth estimates averaging approximately 60%; the values were \$4.902 million for SME A, \$6.675 million for SME B, and \$6.320 million for SME C on a \$10 million project. Using the best-case scenario for each risk factor yielded a minimum cost growth of 8%. This was due to the fact that 5 of the 13 factors did not have a zero cost impact option. At the other end of the spectrum (i.e., the worst-case scenario), the model returned a cost growth of nearly 124%.

These results, based on the SME data, did not yield realistic cost growth predictions. The results indicate that the SMEs did not differentiate between a single risk factor and its effect on other risk factors. For instance, the cost growth provided by the SMEs for the effect of a designer with a "good" past performance was 11.7%. This is possible if the SMEs took into consideration the consequential effect on other factors such as changes, unforeseen site conditions, and duration rather than considering those independent of designer past performance. The cause of this error is a result of the explanation of the process and the SME's inability to limit the cause of the effect. This is consistent with previous research concluding that a decision maker may not be able to disassociate individual parts when their experience deals with the system as a whole (Weir, 2005).

## Phase Two

In an effort to create a model which would allow the project manager to input specific information for any given project under evaluation, the Excel spreadsheet was modified and the Visual Basic code adjusted. The code was written to analyze each cell of the input sheet such that the PM could designate the number of risk levels, probabilities, and impact. If nothing were changed, the program would default to the values assigned by the SMEs. Therefore, a project manager can overwrite the data with specific information and details based on their particular knowledge of the project in question. Using this input, the model can calculate the specific probability distribution and expected cost growth factor for that individual project. New construction for example would have no impact due to asbestos as opposed to a 1960s era building being completely renovated. The program recognizes whether the user has input a one, two, or three tier distribution risk for each factor. Again, using the information provided, the model runs multiple iterative loops in which it calculates, and stores the thousands of possible cost growths. The result is a probability distribution representing the sum of all the cost growth factors.

In addition, the age and duration factors were adjusted. In the previous version, the age of the facility and estimated project duration were unknowns. However, these will be known entities for the PM. Therefore, the probability of these two risk events was set to one and the input sheet was modified to allow the age and duration to be directly input by the PM. To be consistent with the Delphi method, “IF THEN” statements were added to the code to set the cost impact for the age and duration to correspond to the values determined by the SMEs for the appropriate level. The code for the revised

program is shown in Appendix E. For example, if the input age for a facility was between 15 and 30 years old, the impact was assigned a 4.5% cost growth. An example of the revised input sheet is shown in Figure 4.6.

Risk-Based Decision Model											
Original Cost Estimate = \$ 10,000,000											
Age			Weather			Asbestos			Probability % Cost Growth		
New	Nominal	Old	None	Nominal	Severe	None	Minimal	High			
0.6166	0.1667	0.2167	0.2333	0.5	0.2667	0.35	0.35	0.3			
0.500%	4.500%	16.667%	0.000%	2.000%	6.333%	0.500%	5.667%	12.667%			
Sub-Surface			Contractor Experience			Contr Past Performance			Probability % Cost Growth		
None	Minimal	High	Little	Moderate	Significant	Good	Very Good	Exceptional			
0.5	0.2833	0.2167	0.1667	0.5333	0.3	0.2167	0.6333	0.15			
1.167%	5.667%	13.333%	4.667%	1.633%	0.000%	9.333%	3.000%	0.000%			
Contr Management Experience			Design Accuracy			Constructability			Probability % Cost Growth		
Low	Nominal	High	Low	Nominal	High	Easy	Moderate	Difficult			
0.1833	0.5667	0.25	0.5333	0.35	0.1167	0.2833	0.5167	0.2			
7.500%	2.833%	0.000%	15.000%	2.833%	0.000%	0.000%	2.000%	8.667%			
Duration			Changes			Designer Experience			Probability % Cost Growth		
<8M	8-18M	>18M	None	Minimal	Significant	Little	Moderate	Significant			
0.1333	0.4167	0.45	0.1667	0.5	0.3333	0.1833	0.6	0.2167			
1.167%	3.167%	6.833%	4.667%	7.167%	10.667%	12.000%	1.833%	0.000%			
Designer Past Performance											
Good	Very Good	Exceptional									
0.25	0.6	0.15									
11.667%	3.667%	0.000%									
Probability % Cost Growth											

Figure 4.6 User Input Sheet

## **Summary**

The result of the user input model is a tool which will use the specific information provided on the applicable project to return an expected cost growth. The decision maker can then use this information to make a more informed choice as to whether EVM is appropriate for that particular project. This meets the requirement set forth by the revised DoD EVM policy letter for a “Risk-Based Decision.”

## CHAPTER 5

### CONCLUSIONS

The purpose of this research was to develop a model which would quantify the risks associated with a typical construction project in an effort to meet revised requirements set forth by the Department of Defense (DoD) regarding the use of earned value management (EVM). The revised policy stated that the use of EVM for projects under \$20 million would be a “risk-based decision.” Therefore, a spreadsheet-based model was created to evaluate a project manager’s subjective and appropriate knowledge of risk factors concerning a specific project. The output of the model is the expected cost growth associated with the project. Since the cost growth is based on risk factors, the model can be used to determine whether the additional cost of implementing an EVM system is justified. The chapter presents the results of this research by addressing each of the original research questions. In addition, information will be discussed concerning recommendations, strengths and weaknesses, and possible areas of future research.

#### **Question 1**

The first research question asked: *What risk factors affect the cost or schedule of Air Force construction projects?* The results of the literature review revealed that many factors affect the outcome of a construction project. Through the use of the Delphi method with subject matter experts (SMEs), this research identified 13 risk factors that were considered the most relevant and applicable to the cost growth experienced during construction of Air Force (AF) projects. Table 5.1 summarizes these factors.

Table 5.1 Construction Risk Factors

Factors	Sub-Factors
Physical	Age of Facility
	Weather
	Asbestos
	Sub-Surface Conditions
Contractor	Experience
	Past Performance
	Management Experience
Design	Accuracy
	Constructability
	Duration
	Changes
Designer	Experience
	Past Performance

## Question 2

The second research question asked: *What is the probability of occurrence of the identified risk factors?* To answer this question, the Delphi method was used with the SMEs to survey their collective knowledge and experience; consequently, a three-tier risk profile (low, medium, and high) was developed for each identified risk factor. The results provided valuable insight into the likelihood of experiencing a range of each risk factor from a minimal impact, through an expected or moderate impact, to an extreme or high impact. In addition, the research revealed that two of the risk factors (age of facility and duration of the project) would be known entities. Therefore, the specific information could be provided by the project manager with 100% certainty.

### **Question 3**

The third research question asked: *What is the subsequent cost growth due to the occurrence of the risk factor?* With the range of risk levels identified from question two, the SMEs were asked to use their knowledge and experience to estimate the incremental cost growth associated with each risk factor for the three levels of risk. The SMEs were asked to look at each level of each risk factor and estimate an associated cost growth independent of all other factors. However, the SMEs had difficulty compartmentalizing the effects of individual risk factors; they indicated that the impact of a given risk factor was a summation of the impact across the entire project including the effect on other factors. The results, therefore, are biased by approximately ten percent. The correction to this inaccuracy is the ability of the model to use project manager input to recalculate the expected cost growth from information specific to the project in question.

### **Question 4**

The fourth research question asked: *How many AF Construction projects in the last 5-years and those programmed through the FY12 exceed the \$20M threshold or fall into a range which must be evaluated?* From information provided by Cook (2006), the following project counts were accurate as of 15 May 2005. Of 314 military construction projects in the Automated Civil Engineer System database, 125 projects are between \$5 million and \$20 million and 7 Projects are over the \$20 million threshold.



## **Recommendations**

The recommendation of this research is to use the decision tree and model developed from it to provide a quantitative analysis of risk, which can then be used to help determine the applicability of using EVM on construction projects. The decision to use EVM, therefore, implies that sufficient risk is present to warrant the cost of EVM. Due to the cost of implementing EVM, this model should probably be used only on Air Force construction projects with cost estimates over \$5 million. If the cost growth predicted by the model is greater than 5%, the use of EVM is recommended to monitor the risk factors. However, this recommendation should be tempered with the overall risk associated with a given project. In other words, if the calculated cost growth is high but the probability of occurrence is low, the decision-maker may want to forego the use of EVM and the associated costs.

An additional recommendation concerns the model development. Instead of relying on spreadsheet-based calculations, the use of a commercial off-the-shelf decision analysis software package that has the capacity to calculate a large-scale decision tree would be advantageous. A program which offers built-in sensitivity analysis and can handle multiple risk levels would benefit the decision maker greatly.

## **Strengths and Weaknesses**

The primary strength of the model developed in this research is quantification of subjective risk factors. The use of the Delphi method provided the opportunity to develop a consensus regarding appropriate risk factors and the levels of risk associated

with each factor. Another strength is the ability of individual project managers to input project-specific data based on their knowledge and experience.

Several factors were seen as weaknesses impacting this research. The primary concern was the development of relevant data related to the risk factors. The Delphi approach was appropriate but the process requires further refinement. The probabilities of the risk event levels and the associated cost impacts received from the SMEs were not in line with realistic outcomes. The process was inhibited by a lack of face-to-face interaction, the scheduling of time by the SMEs due to busy schedules and temporary duty, the inherent difficulties related to a reliance on e-mail, and the difficulty in compartmentalizing one risk impact independent of the others. The most significant of these sources of error was the compartmentalization of the risk impact.

Subsequent analysis showed that the responses of the SMEs regarding risk impact were actually a cumulative cost impact of all risk factors. In hindsight, the SMEs should have been asked to consider all other factors, besides the risk factor in question, to represent the best-case scenario; in this way, the incremental cost increase would be due only to the specific risk at the specified level. Part of the problem may have been caused by inadequate definitions of the risk factors and their respective risk levels. The validity of the model could be increased through an extensive survey of a broad range of SMEs and through successive phases to narrow the definitions and assumptions. The risk factors themselves could be in question; although validated by the five SMEs, the list is neither exhaustive nor complete.

### **Areas of Future Research**

An area of future research involves the use of a formal survey to query the Civil Engineering career field. The survey could establish relevant risk factors and provide a more extensive knowledge base for the establishment of accurate probabilities and cost growth. Utilizing the Delphi methodology with a large pool of experts and multiple iterations to refine the probabilities and impact would serve to improve the model and help future decision makers.

## Appendix A



ACQUISITION,  
TECHNOLOGY  
AND LOGISTICS

THE UNDER SECRETARY OF DEFENSE  
3010 DEFENSE PENTAGON  
WASHINGTON, D.C. 20301-3010

MAR 7 2005

MEMORANDUM FOR: SEE DISTRIBUTION

SUBJECT: Revision to DoD Earned Value Management Policy

Earned Value Management (EVM) has been an effective management control tool in the Department for the past 37 years. In order to streamline, improve, and increase consistency in EVM implementation and application, I am revising the policy to include the following changes, effective immediately.

1. Cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements valued at or greater than \$20 million in then-year dollars shall implement the American National Standards Institute/Electronic Industries Alliance Standard 748, *Earned Value Management Systems* (ANSI/EIA-748). Cost or incentive contracts, subcontracts, and other agreements valued at or greater than \$50 million in then-year dollars shall have an EVM system that has been formally validated and accepted by the cognizant contracting officer. I intend to review these dollar thresholds, and revise them if necessary, at least every five years.
2. A Contract Performance Report (CPR) (Data Item Description (DID) number DI-MGMT-81466) (previously called the Cost Performance Report) and an Integrated Master Schedule (IMS) (DID number DI-MGMT-81650) shall be required whenever EVM (compliance with ANSI/EIA-748) is required, that is, for cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements valued at or greater than \$20 million in then-year dollars. However, CPR and IMS reporting for cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements valued at less than \$50 million in then-year dollars may be tailored (refer to the DoD Earned Value Management Implementation Guide (EVMIG) for guidance on tailoring reporting). A common work breakdown structure that follows the DoD Work Breakdown Structure Handbook (MIL-HDBK-881) shall be used for the CPR, IMS, and Contractor Cost Data Report (CCDR). The Cost/Schedule Status Report (C/SSR) is rescinded effective immediately (except to the extent that it is required under current contracts) and shall not be used to satisfy the EVM reporting requirement on future contract awards.



3. Integrated Baseline Reviews (IBRs) shall be required whenever EVM (compliance with ANSI/EIA-748) is required, that is, for cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements valued at or greater than \$20 million in then-year dollars.
4. The responsibility and requirement for government surveillance of contracts remains unchanged and shall be based on the effectiveness of the contractor's implementation of internal management controls. Guidance on surveillance activity can be found in the DoD EVMIG.
5. EVM is discouraged on firm-fixed price, level of effort, and time and materials efforts, including contracts, subcontracts, intra-government work agreements, and other agreements, regardless of dollar value. If knowledge by both parties requires access to cost/schedule data, the first action is to re-examine the contract type (e.g., fixed price incentive). However, in extraordinary cases where cost/schedule visibility is required and cannot be obtained using the Truth in Negotiation Act, the program manager shall obtain a waiver for individual contracts from the Milestone Decision Authority. In these cases the program manager will conduct a business case that includes rationale for why a cost or fixed price incentive contract was not an appropriate contracting vehicle.
6. The application of EVM on cost or incentive efforts, including contracts, subcontracts, intra-government work agreements, and other agreements valued at less than \$20 million is optional and is a risk-based decision that is at the discretion of the program manager. A cost-benefit analysis shall be conducted before deciding to implement EVM in these situations. Considerations for determining the efficacy of applying EVM in these situations and guidance for tailoring reporting can be found in the DoD EVMIG.

These changes to EVM policy are not retroactive but shall be implemented on all applicable future contracts that are awarded based on solicitations or requests for proposal issued on or after 30 days from the date of this memorandum. These changes will be included in the next revision of the DoD 5000 series and other acquisition-related documents. While there is no prohibition on negotiating the revised policy into current contracts, the costs associated with changing the EVM requirements on existing contracts shall be borne by the government.


In support of the above policy changes, the Director, Acquisition Resources and Analysis, shall update all pertinent documents, to include DoD Instruction 5000.2, the Defense Acquisition Guidebook, and the CPR and IMS DIDs. The Director, Acquisition Resources and Analysis, shall work with the Director, Defense Procurement and Acquisition Policy, to update the Defense Federal Acquisition Regulation Supplement (DFARS) clauses. The Defense Contract Management Agency shall lead the efforts to

update the DoD EVMIG. The Defense Acquisition University shall update its EVM curriculum.

Until the updated DFARS clauses are coordinated and approved, the existing clauses (252.234-7000 for solicitations and 252.234-7001 for contracts) shall be used. For contracts valued at or greater than \$50 million, these clauses shall be applied directly. For contracts valued at or greater than \$20 million but less than \$50 million, the following paragraph shall be included in the statement of work: *"In regard to DFARS 252.234-7000 and 252.234-7001, the contractor is required to have an Earned Value Management System that complies with ANSI/EIA-748; however, the government will not formally validate/accept the contractor's management system (no formal review)."* While not required, if a risk-based decision is made to require EVM on cost or incentive contracts valued at less than \$20 million, the above paragraph shall also be included in the statement of work.

While it is preferred that Project Management/Earned Value Management costs be charged direct to the contract, the contractor shall follow their accounting policies and procedures.

Questions regarding the revised EVM policy should be directed to Ms. Debbie Tomsic ([deborah.tomsic@osd.mil](mailto:deborah.tomsic@osd.mil)) or Mr. Larry Axtell ([larry.axtell@osd.mil](mailto:larry.axtell@osd.mil)) at (703) 695-0707.

  
Michael W. Wynne  
Acting

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## Appendix B

### PROPOSED NEW EARNED VALUE MANAGEMENT POLICY AND RATIONALE

Fitzgerald's *First Law of Program Management*:<sup>1</sup> ***“There are only two phases to a big military program: Too early to tell and too late to stop. Program advocates like to keep bad news covered up until they have spent so much money that they can advance the sunk-cost argument; that it’s too late to cancel the program because we’ve spent too much already.”***

#### **Benefits of EVM**

Although cynical, the above axiom is all too real and common, not generally because of the deliberate withholding or misrepresentation of information, but because of a simple lack of objective and accurate information on current program status and what that translates to in terms of most likely program outcomes. **Effective management control** is lost the moment accurate information on where a program is and where it will end up is unavailable.

This is simply unacceptable. Management is **accountable** for program outcomes, so it follows that they must have the necessary information that will allow them to effectively control their programs and thus fulfill their responsibility.

If implemented correctly, Earned Value Management (EVM) provides the necessary information to avoid Fitzgerald's *First Law of Program Management*.

This is because EVM is an **integrating** project management tool that **facilitates improved planning and control** of cost, schedule, and work scope. It integrates the functional stovepipes of work scope, schedule, and cost to create an **aggregate picture of performance**, thus providing management with the necessary information to ensure that day-to-day decisions keep performance consistent with program objectives.

To put it another way, EVM provides an **early warning** system for deviations from plan and **quantifies** technical and schedule problems in cost terms, providing a sound and objective basis for considering corrective actions (i.e., work arounds, tradeoffs, etc.). Thus, EVM both **mitigates the risk** of cost and schedule overruns, while also providing a **forecast** of final cost and schedule outcomes.

The following recommendations aim to simplify, improve, and increase consistency in Department of Defense (DoD) EVM policy and processes. They are a reflection of modern day EVM best practices aimed at **bringing EVM within DoD into the 21<sup>st</sup> Century**.



## **EVM Management Standard – Industry Standard**

Recommendation 1: A contractor Earned Value Management System (EVMS) compliant with the current version of American National Standards Institute/Electronic Industries Alliance Standard 748 (ANSI/EIA-748)—a.k.a. Industry Standard (as interpreted by the Guidelines Intent document for complex high-risk projects) will be required whenever EVM is required.

The 32 EVM Guidelines in the Industry Standard do not tell the contractor how to do the work, instead they establish **minimum management control guidelines** for an EVMS. Every EVMS must comply with these guidelines, otherwise there is no **assurance** that the EVM data being provided and relied upon by management is valid. The Guidelines Intent document further interprets the intent of these guidelines.

The Cost/Schedule Status Report (C/SSR) and Cost Performance Report-No Criteria will be eliminated because they do not require contractor compliance with any set of minimum management control principles. Eliminating these categories standardizes EVM reporting requirements and improves the timeliness, accuracy, and reliability of the data created by the EVMS. In addition, eliminating these categories emphasises that DoD is serious about doing EVM correctly (i.e., against a verifiable standard).

## **EVM Reporting**

Recommendation 2: A Contract Performance Report (CPR) and Integrated Master Schedule (IMS) will be required whenever EVM is required.

EVM reporting provides the customer program office **insight** into (i.e., not oversight of) contractor performance. This is vital to enable the customer to provide the specific and timely input that the contractor needs in order to succeed, and to fulfill the DoD program manager's monitoring and reporting role to higher management. It **facilitates communication** between contractor and customer because it presents an accurate picture of project performance at whichever level of the Work Breakdown Structure (WBS) (required) and Organizational Breakdown Structure (OBS) (optional) is being reviewed. It also maximizes **project management efficiency** because EV data allows for management by exception by both the DoD customer and the contractor, while enabling the contractor team to manage the day-to-day work at the task level.

The 32 EVM Guidelines in the Industry Standard do not cover the field of EV data reporting requirements. It is left to the customer to determine the details of the EV data to be reported and the level of analysis required. As a consequence, the customer reporting requirements can require a higher standard of data and analysis. A **higher minimum** standard of data and analysis will be adopted in the updated Data Item Descriptions (DIDs) to reflect **industry best practice** and enable the use of **modern EVM software tools**. These changes are aimed at ensuring contractors and DoD program offices ‘use EV data to manage,’ rather than merely trying to ‘manage the EV data.’ At an appropriate time, the Industry Standard itself may need to be updated, as industry best practice becomes the norm.

**The most significant changes to the updated CPR (to be called Contract Performance Report) include:**

- **Reducing the time period within which EV data and analysis must be available, and strengthening the requirement for digital submission – this will improve the timeliness of reporting, hence increasing its management value.**
- **Requiring more comprehensive data (e.g., separating out General and Administrative (G&A), major subcontractor, material, reprogramming adjustments, and Over Target Baselines; and requiring Performance Measurement Baseline (PMB), Estimate at Completion (EAC), and staffing forecasts monthly for the next six months and monthly, quarterly, or annually to the end of the contract) – this will improve visibility of performance.**
- **Requiring a minimum set of requirements and more comprehensive analysis in Format 5 explanations – this will ensure the data is used, understood, and acted upon.**

**The most significant changes to the updated IMS include:**

- **Mandating and integrating the IMS with the CPR** (e.g., identical contract WBS to be used, concurrent delivery, concurrent analysis) – sound scheduling with critical path analysis has always been a key part of EVM (3 EVM Guidelines deal with it specifically), yet previous policy has overlooked the IMS. Mandating and integrating the IMS with the CPR corrects this oversight.
- **Requiring a fully integrated network of all discrete contract tasks/activities** – this will improve scheduling and eliminate networking of only ‘significant’ interdependencies, an approach that has serious shortcomings, which have been noted on numerous programs.

As a consequence of eliminating the C/SSR category, C/SSR reports are also eliminated. The CPR will remain tailorable and tailoring guidance is being developed for inclusion in the Earned Value Management Implementation Guide (EVMIG). A tailored CPR for

contracts under the \$50M threshold will include as a minimum Format 1 and a tailored Format 5 (Formats 2, 3, and 4 will be optional). Within the parameter of requiring a fully integrated network of all discrete tasks/activities, the IMS will also be tailorable for contracts under the \$50M threshold and tailoring guidance is being developed for inclusion in the EVMIG.

### **EVM Application Threshold**

***Recommendation 3: EVM compliant with the Industry Standard will be required on all cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements greater than or equal to \$20M (optional for contracts of less than 12 months in duration and non-schedule based types of contracts such as time and materials, level of effort, etc.).***

Recommendation 4: EVM for all cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements below \$20M will be a risk-based decision (unless designated as a “major acquisition” in accordance with Office of Management and Budget (OMB) Circular A-11).

**As noted above, EVM is a risk mitigator of cost and schedule overruns. Consequently, where the DoD program manager’s risk analysis has determined that sufficient risk exists to justify a cost or incentive contract, subcontract, or other agreement, then there is also sufficient risk to require EVM. The Research, Development, Test, and Evaluation (RDT&E) versus Procurement/Operations and Maintenance (O&M) distinction is a factor that is taken into account when deciding contract type (i.e., risk), so it is redundant to again make it a factor in determining EVM application.**

**The above application threshold represents a raising of the current C/SSR threshold (from \$6.3M) and a lowering of the current CPR thresholds for RDT&E (from \$73M) and Procurement/O&M (from \$315M). The \$20M threshold aligns with U.S. Department of Energy practice and Australian practice. It is a balanced approach that gives greater discretion to program managers at lower contract values, while also recognizing that the current thresholds are outdated.**

Recommendation 5: EVM for all firm fixed price contracts, subcontracts, intra-government work agreements, and other agreements will be a risk-based decision.

Firm fixed price contracts can still expose the customer to significant schedule risk and even residual cost risk if cost overruns cause the contractor to ‘cut corners’ (e.g., reducing quality as less experienced, lower cost staff perform the work and inferior materials are used, reducing testing, increasing the cost of contract changes and follow-on support contracts to recoup the overrun). Consequently, EVM on firm fixed price contracts is a risk mitigation option that will be available to program managers, but not mandated

(Note: Tailoring guidance for the CPR and IMS on firm fixed price contracts, subcontracts, intra-government work agreements, and other agreements will be provided in the EVMIG, along with guidance that EVM should not be required on contracts of less than 12 months in duration and non-schedule based types of contracts such as time and materials, level of effort, etc. Definitions of the non-schedule based contract types will be included in the guidance.)

## **EVM Implementation**

***Recommendation 6: A validation of the contractor EVMS’s compliance with the Industry Standard will be required on all cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements greater than or equal to \$50M. Validation for all other cost or incentive contracts, subcontracts, intra-government work agreements, and other agreements and for any firm fixed price contracts, subcontracts, intra-government work agreements, and other agreements for which EVM is required will be a risk-based decision.***

Once a contractor’s EVMS is validated and formally accepted by DoD, acceptance will continue to be affirmed via government surveillance. Validation does impose costs. These costs should and will be borne by the government for the following reasons:

- The primary purpose of the validation is to **mitigate** the inherent performance **risk** of any supplier that undertakes a high-risk contract. This is fundamentally a customer responsibility and reflects an appropriate investment in managing taxpayer funds efficiently and effectively. This responsibility can be outsourced to third parties (although note the third bullet below), but contractors must not be allowed to self-regulate; there must be **independent review** of the contractor’s processes to ensure the **integrity** of the validation.
- High-risk contracts impose risk on the customer and this is accepted through cost or incentive type contracts, subcontracts, intra-government work agreements, and other agreements. The necessity to allocate resources to manage this risk is self-evident

and should be explicitly acknowledged and funded accordingly. Funding the validation process **shares some of the costs** of requiring higher standards of project management with contractors.

- DoD validation improves DoD's ability to be an **'informed customer'** – it is important on high-risk contracts for both the customer and contractor to have higher levels of capability, knowledge, and skills. If the customer is not informed, then contractor performance is adversely affected.
- Validation is an important means to facilitate **continuous improvement** because it brings the combined wisdom of a team of experts to provide a reality check on a contractor's EVMS. A balance in the investment required of the customer to undertake this role can be achieved by not requiring validation at the lower value end of the scale, although compliance with the Industry Standard is still required by the contractor.

***Recommendation 7: Government surveillance of the contractor's EVMS will be required whenever EVM is required.***

Government surveillance is required, regardless of whether there is an upfront validation, to provide **assurance** that contractors comply with their contractual obligations and to ensure that the EV data being provided and relied upon by management is valid. The customer must monitor contractor performance in order to fulfill its obligations to the public in managing taxpayer funds. The degree of government surveillance should be based on the effectiveness of the contractor's implementation of internal management controls.

(Note: The EVMIG will mention joint government/contractor surveillance as an option and will reference the National Defense Industrial Association (NDIA) Surveillance Guide. Policy will be developed on what remedies will be available to DoD if surveillance uncovers that a contractor's EVMS is not compliant with the Industry Standard (as interpreted by the Guidelines Intent document for complex high-risk projects), or that the EV data being reported in the CPR and IMS is not compliant with what is required by the respective DIDs.)

***Recommendation 8: An Integrated Baseline Review (IBR) will be required whenever EVM is required.***

IBRs are required whenever EVM is required in order to assess that the contractor baseline for performing the work is achievable and that both the contractor and customer understand all significant risks. An IBR is simply **good practice** at the start of any project regardless of size, and it can be tailored as appropriate to the scope of the work.

#### Implementation of Policy Changes

It is not proposed that the new EVM policy be retroactive; however, the changes are aimed at improving DoD and industry EVM practice, so there will be no prohibition on programs adopting changes and negotiating them into existing contracts, subcontracts, or

other agreements. The duration remaining on a contract and other risk factors should be considered in making the determination to modify an existing contract to require EVM. The costs associated with imposing new or different EVM requirements on existing contracts should and will be borne by the government.

## Appendix C

Project Manager Experience			Project Manager A			Project Manager B			Project Manager C			Average		
Risk Factor	Description	Range	Prob	Cost	Prob	Cost	Prob	Cost	AVE PROB	AVE COST	AVE %			
Age of Facility	0 to 15 years	New	80	\$ 5,000	20	\$ 10,000	85	\$ -	61.67	\$ 5,000	0.500%			
	15 to 30 years	Medium	10	\$ 40,000	30	\$ 25,000	10	\$ 70,000	16.67	\$ 45,000	4.500%			
	over 30 years	Old	10	\$ 100,000	50	\$ 250,000	5	\$ 150,000	21.67	\$ 166,667	16.667%			
Weather		Mild	20	\$ -	25%	\$ -	25	\$ -	15.08	\$ -	0.000%			
	Average weather	Normal	50	\$ 10,000	50%	\$ -	50	\$ 50,000	33.50	\$ 20,000	2.000%			
		Severe	30	\$ 60,000	25%	\$ 30,000	25	\$ 100,000	18.42	\$ 63,333	6.333%			
Asbestos	NONE								15.00	\$0		0.182927		
	Very Little encountered	Low	45	\$ 10,000	10%	\$ 5,000	50	\$ -	31.70	\$ 5,000	0.500%	0.386585		
	Moderate amount	Medium	30	\$ 60,000	50%	\$ 60,000	25	\$ 50,000	18.50	\$ 56,667	5.667%	0.22561		
	High level encountered	High	25	\$ 130,000	40%	\$ 100,000	25	\$ 150,000	16.80	\$ 126,667	12.667%	0.204878		
Sub-Surface (Ground and interior for renovation) (Differing/unforseen sight conditions)	NONE								15.00	\$0		0.152284		
	Little or No unforeseen	Low	40	\$ 15,000	50%	\$ -	60	\$ 20,000	33.50	\$ 11,667	1.167%	0.340102		
	Moderate amount	Medium	35	\$ 55,000	30	\$ 45,000	20	\$ 70,000	28.33	\$ 56,667	5.667%	0.287648		
	High level encountered	High	25	\$ 150,000	20	\$ 100,000	20	\$ 150,000	21.67	\$ 133,333	13.333%	0.219966		
Contractor Experience	Little experience	Low	20	\$ 50,000	5%	\$ 20,000	25	\$ 70,000	15.02	\$ 46,667	4.667%			
	Normal experience	Medium	60	\$ 15,000	50%	\$ 4,000	50	\$ 30,000	36.83	\$ 16,333	1.633%			
	Extensive experience	High	20	\$ -	45%	\$ -	25	\$ -	15.15	\$ -	0.000%			
Contractor Past Performance	Poor performance	Low	25	\$ 80,000	10%	\$ 100,000	30	\$ 100,000	18.37	\$ 93,333	9.333%			
	Normal performance	Medium	55	\$ 20,000	75%	\$ 20,000	60	\$ 50,000	38.58	\$ 30,000	3.000%			
	Exceptional performance	High	20	\$ -	15%	\$ -	10	\$ -	10.05	\$ -	0.000%			
Contractor Management Experience	Little experience	Low	30	\$ 75,000	15	\$ 50,000	10	\$ 100,000	18.33	\$ 75,000	7.500%			
	Normal experience	Medium	50	\$ 20,000	60	\$ 15,000	60	\$ 50,000	56.67	\$ 28,333	2.833%			
	Extensive experience	High	20	\$ -	25	\$ -	30	\$ -	25.00	\$ -	0.000%			
Designer Experience	Little experience	Low	15	\$ 40,000	10	\$ 250,000	30	\$ 70,000	18.33	\$ 120,000	12.000%			
	Normal experience	Medium	60	\$ 15,000	60	\$ 10,000	60	\$ 30,000	60.00	\$ 18,333	1.833%			
	Extensive experience	High	25	\$ -	30	\$ -	10	\$ -	21.67	\$ -	0.000%			
Designer Past Performance	Poor performance	Low	15	\$ 50,000	30	\$ 200,000	30	\$ 100,000	25.00	\$ 116,667	11.667%			
	Normal performance	Medium	60	\$ 20,000	60	\$ 40,000	60	\$ 50,000	60.00	\$ 36,667	3.667%			
	Exceptional performance	High	25	\$ -	10	\$ -	10	\$ -	15.00	\$ -	0.000%			
Design Accuracy	Not accurate	Low	60	\$ 100,000	50	\$ 250,000	60	\$ 100,000	56.67	\$ 150,000	15.000%			
	Accurate	Medium	40	\$ 35,000	30	\$ 10,000	35	\$ 40,000	35.00	\$ 28,333	2.833%			
	Very accurate	High	10	\$ -	20	\$ -	5	\$ -	11.67	\$ -	0.000%			
Design Constructability (Type of Facility)	Simple Design	Low	15	\$ -	40	\$ -	30	\$ -	28.33	\$ -	0.000%			
	Normal Design	Medium	75	\$ 30,000	20	\$ -	60	\$ 30,000	51.67	\$ 20,000	2.000%			
	Highly Technical/Intricate	High	10	\$ 85,000	40	\$ 25,000	10	\$ 150,000	20.00	\$ 86,667	8.667%			
Project Duration	0-8 months	Low	5	\$ 10,000	20	\$ 5,000	15	\$ 20,000	13.33	\$ 11,667	1.167%			
	8-18 months	Medium	35	\$ 30,000	60	\$ 15,000	30	\$ 50,000	41.67	\$ 31,667	3.167%			
	Over 18 months	High	60	\$ 75,000	20	\$ 30,000	55	\$ 100,000	45.00	\$ 68,333	6.833%			
Opportunity for Design Changes	NONE								15.00	\$0		0.182927		
	Little user input	Low	15	\$ 20,000	20%	\$ 20,000	15	\$ 100,000	10.07	\$ 46,667	4.667%	0.122764		
	Moderate user interaction	Medium	70	\$ 65,000	20%	\$ 100,000	60	\$ 50,000	43.40	\$ 71,667	7.167%	0.529268		
	Extensive user input	High	15	\$ 100,000	60%	\$ 200,000	25	\$ 20,000	13.53	\$ 106,667	10.667%	0.165041		

## Appendix D

```
Sub test()
Dim arraysize As Long
Start = Timer
Dim temptree(1, 16) As Single
'build one for each chance node
Dim age(3, 2) As Double
Dim weather(3, 2) As Double
Dim asbestos(3, 2) As Double
Dim subsurface(3, 2) As Double
Dim contractorexperience(3, 2) As Double
Dim contractorpastperformance(3, 2) As Double
Dim contractormanagementexpertise(3, 2) As Double
Dim designaccuracy(3, 2) As Double
Dim constructability(3, 2) As Double
Dim duration(3, 2) As Double
Dim changes(3, 2) As Double
Dim designerexperience(3, 2) As Double
Dim designerpastperformance(3, 2) As Double
Dim designerproximity(3, 2) As Double
Dim Cumprob() As Single

'constants
cost = Sheets("CGF").Cells(2, 6)

'build for each level
'first number is level
'second number is 1=prob 2 = outcome

'User input
agecount = 0
colnum = 1
While Sheets("CGF").Cells(6, colnum) <> ""
    agecount = agecount + 1
    colnum = colnum + 1
Wend

'User input
weathercount = 0
colnum = 5
While Sheets("CGF").Cells(6, colnum) <> ""
    weathercount = weathercount + 1
    colnum = colnum + 1
Wend

'User input
asbestoscount = 0
colnum = 9
While Sheets("CGF").Cells(6, colnum) <> ""
    asbestoscount = asbestoscount + 1
```



```
    colnum = colnum + 1
Wend
```

```
'User input
sscount = 0
colnum = 1
While Sheets("CGF").Cells(11, colnum) <> ""
    sscount = sscount + 1
    colnum = colnum + 1
Wend
```

```
'User input
cecount = 0
colnum = 5
While Sheets("CGF").Cells(11, colnum) <> ""
    cecount = cecount + 1
    colnum = colnum + 1
Wend
```

```
'User input
cppcount = 0
colnum = 9
While Sheets("CGF").Cells(11, colnum) <> ""
    cppcount = cppcount + 1
    colnum = colnum + 1
Wend
```

```
'User input
cmecount = 0
colnum = 1
While Sheets("CGF").Cells(16, colnum) <> ""
    cmecount = cmecount + 1
    colnum = colnum + 1
Wend
```

```
'User input
dacount = 0
colnum = 5
While Sheets("CGF").Cells(16, colnum) <> ""
    dacount = dacount + 1
    colnum = colnum + 1
Wend
```

```
'User input
cocount = 0
colnum = 9
While Sheets("CGF").Cells(16, colnum) <> ""
    cocount = cocount + 1
    colnum = colnum + 1
Wend
```

```

'User input
ducount = 0
colnum = 1
While Sheets("CGF").Cells(21, colnum) <> ""
    ducount = ducount + 1
    colnum = colnum + 1
Wend

```

```

'User input
chcount = 0
colnum = 5
While Sheets("CGF").Cells(21, colnum) <> ""
    chcount = chcount + 1
    colnum = colnum + 1
Wend

```

```

'User input
decount = 0
colnum = 9
While Sheets("CGF").Cells(21, colnum) <> ""
    decount = decount + 1
    colnum = colnum + 1
Wend

```

```

'User input
dppcount = 0
colnum = 1
While Sheets("CGF").Cells(26, colnum) <> ""
    dppcount = dppcount + 1
    colnum = colnum + 1
Wend

```

```

age(1, 1) = Sheets("CGF").Cells(6, 1)
age(1, 2) = Sheets("CGF").Cells(7, 1) * cost
age(2, 1) = Sheets("CGF").Cells(6, 2)
age(2, 2) = Sheets("CGF").Cells(7, 2) * cost
age(3, 1) = Sheets("CGF").Cells(6, 3)
age(3, 2) = Sheets("CGF").Cells(7, 3) * cost

```

```

weather(1, 1) = Sheets("CGF").Cells(6, 5)
weather(1, 2) = Sheets("CGF").Cells(7, 5) * cost
weather(2, 1) = Sheets("CGF").Cells(6, 6)
weather(2, 2) = Sheets("CGF").Cells(7, 6) * cost
weather(3, 1) = Sheets("CGF").Cells(6, 7)
weather(3, 2) = Sheets("CGF").Cells(7, 7) * cost

```

asbestos(1, 1) = Sheets("CGF").Cells(6, 9)  
asbestos(1, 2) = Sheets("CGF").Cells(7, 9) \* cost  
asbestos(2, 1) = Sheets("CGF").Cells(6, 10)  
asbestos(2, 2) = Sheets("CGF").Cells(7, 10) \* cost  
asbestos(3, 1) = Sheets("CGF").Cells(6, 11)  
asbestos(3, 2) = Sheets("CGF").Cells(7, 11) \* cost

subsurface(1, 1) = Sheets("CGF").Cells(11, 1)  
subsurface(1, 2) = Sheets("CGF").Cells(12, 1) \* cost  
subsurface(2, 1) = Sheets("CGF").Cells(11, 2)  
subsurface(2, 2) = Sheets("CGF").Cells(12, 2) \* cost  
subsurface(3, 1) = Sheets("CGF").Cells(11, 3)  
subsurface(3, 2) = Sheets("CGF").Cells(12, 3) \* cost

contractorexperience(1, 1) = Sheets("CGF").Cells(11, 5)  
contractorexperience(1, 2) = Sheets("CGF").Cells(12, 5) \* cost  
contractorexperience(2, 1) = Sheets("CGF").Cells(11, 6)  
contractorexperience(2, 2) = Sheets("CGF").Cells(12, 6) \* cost  
contractorexperience(3, 1) = Sheets("CGF").Cells(11, 7)  
contractorexperience(3, 2) = Sheets("CGF").Cells(12, 7) \* cost

contractorpastperformance(1, 1) = Sheets("CGF").Cells(11, 9)  
contractorpastperformance(1, 2) = Sheets("CGF").Cells(12, 9) \* cost  
contractorpastperformance(2, 1) = Sheets("CGF").Cells(11, 10)  
contractorpastperformance(2, 2) = Sheets("CGF").Cells(12, 10) \* cost  
contractorpastperformance(3, 1) = Sheets("CGF").Cells(11, 11)  
contractorpastperformance(3, 2) = Sheets("CGF").Cells(12, 11) \* cost

contractormanagementexpertise(1, 1) = Sheets("CGF").Cells(16, 1)  
contractormanagementexpertise(1, 2) = Sheets("CGF").Cells(17, 1) \* cost  
contractormanagementexpertise(2, 1) = Sheets("CGF").Cells(16, 2)  
contractormanagementexpertise(2, 2) = Sheets("CGF").Cells(17, 2) \* cost  
contractormanagementexpertise(3, 1) = Sheets("CGF").Cells(16, 3)  
contractormanagementexpertise(3, 2) = Sheets("CGF").Cells(17, 3) \* cost

designaccuracy(1, 1) = Sheets("CGF").Cells(16, 5)  
designaccuracy(1, 2) = Sheets("CGF").Cells(17, 5) \* cost  
designaccuracy(2, 1) = Sheets("CGF").Cells(16, 6)  
designaccuracy(2, 2) = Sheets("CGF").Cells(17, 6) \* cost  
designaccuracy(3, 1) = Sheets("CGF").Cells(16, 7)  
designaccuracy(3, 2) = Sheets("CGF").Cells(17, 7) \* cost

constructability(1, 1) = Sheets("CGF").Cells(16, 9)  
constructability(1, 2) = Sheets("CGF").Cells(17, 9) \* cost  
constructability(2, 1) = Sheets("CGF").Cells(16, 10)

**constructability(2, 2) = Sheets("CGF").Cells(17, 10) \* cost**  
**constructability(3, 1) = Sheets("CGF").Cells(16, 11)**  
**constructability(3, 2) = Sheets("CGF").Cells(17, 11) \* cost**

**duration(1, 1) = Sheets("CGF").Cells(21, 1)**  
**duration(1, 2) = Sheets("CGF").Cells(22, 1) \* cost**  
**duration(2, 1) = Sheets("CGF").Cells(21, 2)**  
**duration(2, 2) = Sheets("CGF").Cells(22, 2) \* cost**  
**duration(3, 1) = Sheets("CGF").Cells(21, 3)**  
**duration(3, 2) = Sheets("CGF").Cells(22, 3) \* cost**

**changes(1, 1) = Sheets("CGF").Cells(21, 5)**  
**changes(1, 2) = Sheets("CGF").Cells(22, 5) \* cost**  
**changes(2, 1) = Sheets("CGF").Cells(21, 6)**  
**changes(2, 2) = Sheets("CGF").Cells(22, 6) \* cost**  
**changes(3, 1) = Sheets("CGF").Cells(21, 7)**  
**changes(3, 2) = Sheets("CGF").Cells(22, 7) \* cost**

**designerexperience(1, 1) = Sheets("CGF").Cells(21, 9)**  
**designerexperience(1, 2) = Sheets("CGF").Cells(22, 9) \* cost**  
**designerexperience(2, 1) = Sheets("CGF").Cells(21, 10)**  
**designerexperience(2, 2) = Sheets("CGF").Cells(22, 10) \* cost**  
**designerexperience(3, 1) = Sheets("CGF").Cells(21, 11)**  
**designerexperience(3, 2) = Sheets("CGF").Cells(22, 11) \* cost**

**designerpastperformance(1, 1) = Sheets("CGF").Cells(26, 1)**  
**designerpastperformance(1, 2) = Sheets("CGF").Cells(27, 1) \* cost**  
**designerpastperformance(2, 1) = Sheets("CGF").Cells(26, 2)**  
**designerpastperformance(2, 2) = Sheets("CGF").Cells(27, 2) \* cost**  
**designerpastperformance(3, 1) = Sheets("CGF").Cells(26, 3)**  
**designerpastperformance(3, 2) = Sheets("CGF").Cells(27, 3) \* cost**

**'designerproximity(1, 1) = Sheets("CGF").Cells(26, 5)**  
**'designerproximity(1, 2) = Sheets("CGF").Cells(27, 5) \* cost**  
**'designerproximity(2, 1) = Sheets("CGF").Cells(26, 6)**  
**'designerproximity(2, 2) = Sheets("CGF").Cells(27, 6) \* cost**  
**'designerproximity(3, 1) = Sheets("CGF").Cells(26, 7)**  
**'designerproximity(3, 2) = Sheets("CGF").Cells(27, 7) \* cost**

**ev = 0**  
**For i = 1 To agecount**  
    **For j = 1 To weathercount**  
        **For k = 1 To asbestoscount**  
            **For L = 1 To sscount**  
                **For m = 1 To cecount**  
                    **For n = 1 To cppcount**  
                        **For o = 1 To cmecount**

```

For p = 1 To dacount
  For q = 1 To cocount
    For R = 1 To ducount
      For s = 1 To chcount
        For t = 1 To decount
          For u = 1 To dppcount
            'For v = 1 To 3
              Count = Count + 1
              'build one statement for each chance node
              storetree(Count, 1) = i
              storetree(Count, 2) = j
              storetree(Count, 3) = k
              storetree(Count, 4) = L
              storetree(Count, 5) = m
              storetree(Count, 6) = n
              storetree(Count, 7) = o
              storetree(Count, 8) = p
              storetree(Count, 9) = q
              storetree(Count, 10) = R
              storetree(Count, 11) = s
              storetree(Count, 12) = t
              storetree(Count, 13) = u
              storetree(Count, 14) = 0
              'build one equation for prob and outcome
              Prob = age(i, 1) * weather(j, 1) * asbestos(k, 1) *
subsurface(L, 1) * contractorexperience(m, 1) * contractorpastperformance(n, 1) *
contractormanagementexpertise(o, 1) * designaccuracy(p, 1) * constructability(q, 1) *
duration(R, 1) * changes(s, 1) * designerexperience(t, 1) * designerpastperformance(u, 1)
              outcome = age(i, 2) + weather(j, 2) + asbestos(k, 2) +
subsurface(L, 2) + contractorexperience(m, 2) + contractorpastperformance(n, 2) +
contractormanagementexpertise(o, 2) + designaccuracy(p, 2) + constructability(q, 2) +
duration(R, 2) + changes(s, 2) + designerexperience(t, 2) + designerpastperformance(u, 2)

              ev = ev + Prob * outcome
              storetree(Count, 15) = Prob
              storetree(Count, 16) = outcome
            'Next
          Next
        Next
      Next
    Next
  Next
Next
arraysize = Count

```

**Sheets(2).Cells(1, 4) = ev**

**Finish = Timer ' Set end time.**

**totaltime = (Finish - Start) / 60**

**Sheets(2).Cells(1, 6) = "It took " & Format(totaltime, "#####.##") & " minutes to run"**

**'sort storetree**

**QuickSortL 1, arraysize, cost**

**'Sheets("sheet2").Range("A1:D6200").Select**

**Selection.ClearContents**

**Count = 1**

**total = 1**

**Cumprobttotal = 0**

**While Count <= arraysize**

**ReDim Preserve Cumprob(3, total)**

**temp = storetree(Count, 16)**

**Prob = 0**

**While storetree(Count, 16) = temp**

**Cumprobttotal = Cumprobttotal + storetree(Count, 15)**

**Prob = Prob + storetree(Count, 15)**

**Count = Count + 1**

**Wend**

**Cumprob(1, total) = temp**

**Cumprob(2, total) = Prob**

**Cumprob(3, total) = Cumprobttotal**

**total = total + 1**

**Wend**

**Sheets(2).Cells(1, 4) = ev**

**For i = 1 To total - 1**

**Sheets(2).Cells(i, 1) = Cumprob(1, i)**

**Sheets(2).Cells(i, 2) = Cumprob(2, i)**

**Sheets(2).Cells(i, 3) = Cumprob(3, i)**

**Next i**

**End Sub**

**Sub QuickSortL(L As Long, R As Long, cost)**

**storetree(L - 1, 16) = 0**

**storetree(R + 1, 16) = 10000 \* cost**

**QuickL L, R**

**InsertL L, R**

**End Sub**

**Sub QuickL(L As Long, R As Long)**

**Dim MED As Long**

**Dim LP As Long**

**Dim RP As Long**

**Dim Pivot As Long**

**Dim TMP As Double**

```
If R - L > 12 Then
  MED = (L + R) \ 2
  For i = 1 To 16
    TMP = storetree(MED, i)
    storetree(MED, i) = storetree(L, i)
    storetree(L, i) = TMP
  Next i
  If storetree(L + 1, 16) > storetree(R, 16) Then
    For i = 1 To 16
      TMP = storetree(L + 1, i)
      storetree(L + 1, i) = storetree(R, i)
      storetree(R, i) = TMP
    Next i
  End If
  If storetree(L, 16) > storetree(R, 16) Then
    For i = 1 To 16
      TMP = storetree(L, i)
      storetree(L, i) = storetree(R, i)
      storetree(R, i) = TMP
    Next i
  End If
  If storetree(L + 1, 16) > storetree(L, 16) Then
    For i = 1 To 16
      TMP = storetree(L + 1, i)
      storetree(L + 1, i) = storetree(L, i)
      storetree(L, i) = TMP
    Next i
  End If
  Pivot = storetree(L, 16)
  LP = L
  RP = R + 1
  Do
    Do
      LP = LP + 1
    Loop While storetree(LP, 16) < Pivot
    Do
      RP = RP - 1
    Loop While storetree(RP, 16) > Pivot
    If RP <= LP Then Exit Do
    For i = 1 To 16
      TMP = storetree(LP, i)
      storetree(LP, i) = storetree(RP, i)
      storetree(RP, i) = TMP
    Next i
  Loop
  For i = 1 To 16
    TMP = storetree(L, i)
    storetree(L, i) = storetree(RP, i)
    storetree(RP, i) = TMP
```

```

    Next i
    If (RP - 1) - L < R - LP Then
        QuickL L, RP - 1
        QuickL LP, R
    Else
        QuickL LP, R
        QuickL L, RP - 1
    End If
End If
End Sub

Sub InsertL(L As Long, R As Long)
    Dim LP As Long
    Dim RP As Long
    Dim TMP(1, 16) As Double

    For RP = L + 1 To R
        For i = 1 To 16
            TMP(1, i) = storetree(RP, i)
        Next i
        For LP = RP To L + 1 Step -1
            If TMP(1, 16) < storetree(LP - 1, 16) Then
                For i = 1 To 16
                    storetree(LP, i) = storetree(LP - 1, i)
                Next i
            Else
                Exit For
            End If
        Next LP
        For i = 1 To 16
            storetree(LP, i) = TMP(1, i)
        Next i
    Next RP
End Sub

```



## Appendix E

**Dim storetree(1600000, 16) As Single**

**Sub test()**

**Dim arraysize As Long**

**Start = Timer**

**Dim temptree(1, 16) As Single**

**'build one for each chance node**

**Dim age(3, 2) As Double**

**Dim weather(3, 2) As Double**

**Dim asbestos(3, 2) As Double**

**Dim subsurface(3, 2) As Double**

**Dim contractorexperience(3, 2) As Double**

**Dim contractorpastperformance(3, 2) As Double**

**Dim contractormanagementexpertise(3, 2) As Double**

**Dim designaccuracy(3, 2) As Double**

**Dim constructability(3, 2) As Double**

**Dim duration(3, 2) As Double**

**Dim changes(3, 2) As Double**

**Dim designerexperience(3, 2) As Double**

**Dim designerpastperformance(3, 2) As Double**

**Dim Cumprob() As Single**

**'constants**

**cost = Sheets("CGF").Cells(2, 10)**

**'build for each level**

**'first number is level**

**'second number is 1=prob 2 = outcome**

**'User input for Age**

**If Sheets("CGF").Cells(6, 4) = 0 Then**

**age(1, 1) = 1**

**age(1, 2) = 0**

**agecount = 1**

**End If**

**If Sheets("CGF").Cells(6, 4) > 0 And Sheets("CGF").Cells(6, 4) < 15 Then**

**age(1, 1) = 1**

**age(1, 2) = 0.005 \* cost**

**agecount = 1**

**End If**

**If Sheets("CGF").Cells(6, 4) >= 15 And Sheets("CGF").Cells(6, 4) < 30 Then**

**age(1, 1) = 1**

**age(1, 2) = 0.045 \* cost**

**agecount = 1**

**End If**

**If Sheets("CGF").Cells(6, 4) >= 30 Then**

```

    age(1, 1) = 1
    age(1, 2) = 0.16667 * cost
    agecount = 1
End If

```

```

'User input for Duration
If Sheets("CGF").Cells(21, 4) = 0 Then
    duration(1, 1) = 1
    duration(1, 2) = 0
    ducount = 1
End If

```

```

If Sheets("CGF").Cells(21, 4) > 0 And Sheets("CGF").Cells(21, 4) < 8 Then
    duration(1, 1) = 1
    duration(1, 2) = 0.005 * cost
    ducount = 1
End If

```

```

If Sheets("CGF").Cells(21, 4) >= 8 And Sheets("CGF").Cells(21, 4) < 18 Then
    duration(1, 1) = 1
    duration(1, 2) = 0.045 * cost
    ducount = 1
End If

```

```

If Sheets("CGF").Cells(21, 4) >= 18 Then
    duration(1, 1) = 1
    duration(1, 2) = 0.16667 * cost
    ducount = 1
End If

```

```

'User input
weathercount = 0
colnum = 9
While Sheets("CGF").Cells(6, colnum) <> ""
    weathercount = weathercount + 1
    colnum = colnum + 1
Wend

```

```

'User input
asbestoscount = 0
colnum = 15
While Sheets("CGF").Cells(6, colnum) <> ""
    asbestoscount = asbestoscount + 1
    colnum = colnum + 1
Wend

```

```

'User input
sscount = 0
colnum = 3

```

```

While Sheets("CGF").Cells(11, colnum) <> ""
    sscount = sscount + 1
    colnum = colnum + 1
Wend

```

```

'User input
cecount = 0
colnum = 9
While Sheets("CGF").Cells(11, colnum) <> ""
    cecount = cecount + 1
    colnum = colnum + 1
Wend

```

```

'User input
cppcount = 0
colnum = 15
While Sheets("CGF").Cells(11, colnum) <> ""
    cppcount = cppcount + 1
    colnum = colnum + 1
Wend

```

```

'User input
cmecount = 0
colnum = 3
While Sheets("CGF").Cells(16, colnum) <> ""
    cmecount = cmecount + 1
    colnum = colnum + 1
Wend

```

```

'User input
dacount = 0
colnum = 9
While Sheets("CGF").Cells(16, colnum) <> ""
    dacount = dacount + 1
    colnum = colnum + 1
Wend

```

```

'User input
cocount = 0
colnum = 15
While Sheets("CGF").Cells(16, colnum) <> ""
    cocount = cocount + 1
    colnum = colnum + 1
Wend

```

```

'User input
chcount = 0
colnum = 9
While Sheets("CGF").Cells(21, colnum) <> ""

```

```

    chcount = chcount + 1
    colnum = colnum + 1
Wend

```

```

'User input
decount = 0
colnum = 15
While Sheets("CGF").Cells(21, colnum) <> ""
    decount = decount + 1
    colnum = colnum + 1
Wend

```

```

'User input
dppcount = 0
colnum = 3
While Sheets("CGF").Cells(26, colnum) <> ""
    dppcount = dppcount + 1
    colnum = colnum + 1
Wend

```

```

weather(1, 1) = Sheets("CGF").Cells(6, 9)
weather(1, 2) = Sheets("CGF").Cells(7, 9) * cost
weather(2, 1) = Sheets("CGF").Cells(6, 10)
weather(2, 2) = Sheets("CGF").Cells(7, 10) * cost
weather(3, 1) = Sheets("CGF").Cells(6, 11)
weather(3, 2) = Sheets("CGF").Cells(7, 11) * cost

```

```

asbestos(1, 1) = Sheets("CGF").Cells(6, 15)
asbestos(1, 2) = Sheets("CGF").Cells(7, 15) * cost
asbestos(2, 1) = Sheets("CGF").Cells(6, 16)
asbestos(2, 2) = Sheets("CGF").Cells(7, 16) * cost
asbestos(3, 1) = Sheets("CGF").Cells(6, 17)
asbestos(3, 2) = Sheets("CGF").Cells(7, 17) * cost

```

```

subsurface(1, 1) = Sheets("CGF").Cells(11, 3)
subsurface(1, 2) = Sheets("CGF").Cells(12, 3) * cost
subsurface(2, 1) = Sheets("CGF").Cells(11, 4)
subsurface(2, 2) = Sheets("CGF").Cells(12, 4) * cost
subsurface(3, 1) = Sheets("CGF").Cells(11, 5)
subsurface(3, 2) = Sheets("CGF").Cells(12, 5) * cost

```

```

contractorexperience(1, 1) = Sheets("CGF").Cells(11, 9)
contractorexperience(1, 2) = Sheets("CGF").Cells(12, 9) * cost
contractorexperience(2, 1) = Sheets("CGF").Cells(11, 10)
contractorexperience(2, 2) = Sheets("CGF").Cells(12, 10) * cost
contractorexperience(3, 1) = Sheets("CGF").Cells(11, 11)
contractorexperience(3, 2) = Sheets("CGF").Cells(12, 11) * cost

```

**contractorpastperformance(1, 1) = Sheets("CGF").Cells(11, 15)**  
**contractorpastperformance(1, 2) = Sheets("CGF").Cells(12, 15) \* cost**  
**contractorpastperformance(2, 1) = Sheets("CGF").Cells(11, 16)**  
**contractorpastperformance(2, 2) = Sheets("CGF").Cells(12, 16) \* cost**  
**contractorpastperformance(3, 1) = Sheets("CGF").Cells(11, 17)**  
**contractorpastperformance(3, 2) = Sheets("CGF").Cells(12, 17) \* cost**

**contractormanagementexpertise(1, 1) = Sheets("CGF").Cells(16, 3)**  
**contractormanagementexpertise(1, 2) = Sheets("CGF").Cells(17, 3) \* cost**  
**contractormanagementexpertise(2, 1) = Sheets("CGF").Cells(16, 4)**  
**contractormanagementexpertise(2, 2) = Sheets("CGF").Cells(17, 4) \* cost**  
**contractormanagementexpertise(3, 1) = Sheets("CGF").Cells(16, 5)**  
**contractormanagementexpertise(3, 2) = Sheets("CGF").Cells(17, 5) \* cost**

**designaccuracy(1, 1) = Sheets("CGF").Cells(16, 9)**  
**designaccuracy(1, 2) = Sheets("CGF").Cells(17, 9) \* cost**  
**designaccuracy(2, 1) = Sheets("CGF").Cells(16, 10)**  
**designaccuracy(2, 2) = Sheets("CGF").Cells(17, 10) \* cost**  
**designaccuracy(3, 1) = Sheets("CGF").Cells(16, 11)**  
**designaccuracy(3, 2) = Sheets("CGF").Cells(17, 11) \* cost**

**constructability(1, 1) = Sheets("CGF").Cells(16, 15)**  
**constructability(1, 2) = Sheets("CGF").Cells(17, 15) \* cost**  
**constructability(2, 1) = Sheets("CGF").Cells(16, 16)**  
**constructability(2, 2) = Sheets("CGF").Cells(17, 16) \* cost**  
**constructability(3, 1) = Sheets("CGF").Cells(16, 17)**  
**constructability(3, 2) = Sheets("CGF").Cells(17, 17) \* cost**

**changes(1, 1) = Sheets("CGF").Cells(21, 9)**  
**changes(1, 2) = Sheets("CGF").Cells(22, 9) \* cost**  
**changes(2, 1) = Sheets("CGF").Cells(21, 10)**  
**changes(2, 2) = Sheets("CGF").Cells(22, 10) \* cost**  
**changes(3, 1) = Sheets("CGF").Cells(21, 11)**  
**changes(3, 2) = Sheets("CGF").Cells(22, 11) \* cost**

**designerexperience(1, 1) = Sheets("CGF").Cells(21, 15)**  
**designerexperience(1, 2) = Sheets("CGF").Cells(22, 15) \* cost**  
**designerexperience(2, 1) = Sheets("CGF").Cells(21, 16)**  
**designerexperience(2, 2) = Sheets("CGF").Cells(22, 16) \* cost**  
**designerexperience(3, 1) = Sheets("CGF").Cells(21, 17)**  
**designerexperience(3, 2) = Sheets("CGF").Cells(22, 17) \* cost**

**designerpastperformance(1, 1) = Sheets("CGF").Cells(26, 3)**  
**designerpastperformance(1, 2) = Sheets("CGF").Cells(27, 3) \* cost**

```

designerpastperformance(2, 1) = Sheets("CGF").Cells(26, 4)
designerpastperformance(2, 2) = Sheets("CGF").Cells(27, 4) * cost
designerpastperformance(3, 1) = Sheets("CGF").Cells(26, 5)
designerpastperformance(3, 2) = Sheets("CGF").Cells(27, 5) * cost

```

```

ev = 0
For i = 1 To agecount
  For j = 1 To weathercount
    For k = 1 To asbestoscount
      For L = 1 To sscount
        For m = 1 To cecount
          For n = 1 To cppcount
            For o = 1 To cmecount
              For p = 1 To dacount
                For q = 1 To cocount
                  For R = 1 To duccount
                    For s = 1 To chcount
                      For t = 1 To decount
                        For u = 1 To dppcount
                          'For v = 1 To 3
                          Count = Count + 1
                          'build one statement for each chance node
                          storetree(Count, 1) = i
                          storetree(Count, 2) = j
                          storetree(Count, 3) = k
                          storetree(Count, 4) = L
                          storetree(Count, 5) = m
                          storetree(Count, 6) = n
                          storetree(Count, 7) = o
                          storetree(Count, 8) = p
                          storetree(Count, 9) = q
                          storetree(Count, 10) = R
                          storetree(Count, 11) = s
                          storetree(Count, 12) = t
                          storetree(Count, 13) = u
                          storetree(Count, 14) = 0
                          'build one equation for prob and outcome
                          Prob = age(i, 1) * weather(j, 1) * asbestos(k, 1) *
subsurface(L, 1) * contractorexperience(m, 1) * contractorpastperformance(n, 1) *
contractormanagementexpertise(o, 1) * designaccuracy(p, 1) * constructability(q, 1) *
duration(R, 1) * changes(s, 1) * designerexperience(t, 1) * designerpastperformance(u, 1)
                          outcome = age(i, 2) + weather(j, 2) + asbestos(k, 2) +
subsurface(L, 2) + contractorexperience(m, 2) + contractorpastperformance(n, 2) +
contractormanagementexpertise(o, 2) + designaccuracy(p, 2) + constructability(q, 2) +
duration(R, 2) + changes(s, 2) + designerexperience(t, 2) + designerpastperformance(u, 2)

                          ev = ev + Prob * outcome
                          storetree(Count, 15) = Prob
                          storetree(Count, 16) = outcome

```

```

'Next
Next
Next
Next
Next
Next
Next
Next
Next
Next
Next
Next
Next
Next
Next
Next
Next
arraysize = Count
Sheets(2).Cells(1, 4) = ev

Finish = Timer ' Set end time.
totaltime = (Finish - Start) / 60
Sheets(2).Cells(1, 6) = "It took " & Format(totaltime, "#####.##") & " minutes to run"

'sort storetree
QuickSortL 1, arraysize, cost

Sheets(2).Range("A1:D62000").Select
Selection.ClearContents
Count = 1
total = 1
Cumprobttotal = 0
While Count <= arraysize
    ReDim Preserve Cumprob(3, total)
    temp = storetree(Count, 16)
    Prob = 0
    While storetree(Count, 16) = temp
        Cumprobttotal = Cumprobttotal + storetree(Count, 15)
        Prob = Prob + storetree(Count, 15)
        Count = Count + 1
    Wend
    Cumprob(1, total) = temp
    Cumprob(2, total) = Prob
    Cumprob(3, total) = Cumprobttotal
    total = total + 1
Wend
Sheets(2).Cells(1, 4) = ev

For i = 1 To total - 1
    Sheets(2).Cells(i, 1) = Cumprob(1, i)
    Sheets(2).Cells(i, 2) = Cumprob(2, i)
    Sheets(2).Cells(i, 3) = Cumprob(3, i)
Next i

```

**End Sub**

**Sub QuickSortL(L As Long, R As Long, cost)**

**storetree(L - 1, 16) = 0**

**storetree(R + 1, 16) = 10000 \* cost**

**QuickL L, R**

**InsertL L, R**

**End Sub**

**Sub QuickL(L As Long, R As Long)**

**Dim MED As Long**

**Dim LP As Long**

**Dim RP As Long**

**Dim Pivot As Long**

**Dim TMP As Double**

**If R - L > 12 Then**

**MED = (L + R) \ 2**

**For i = 1 To 16**

**TMP = storetree(MED, i)**

**storetree(MED, i) = storetree(L, i)**

**storetree(L, i) = TMP**

**Next i**

**If storetree(L + 1, 16) > storetree(R, 16) Then**

**For i = 1 To 16**

**TMP = storetree(L + 1, i)**

**storetree(L + 1, i) = storetree(R, i)**

**storetree(R, i) = TMP**

**Next i**

**End If**

**If storetree(L, 16) > storetree(R, 16) Then**

**For i = 1 To 16**

**TMP = storetree(L, i)**

**storetree(L, i) = storetree(R, i)**

**storetree(R, i) = TMP**

**Next i**

**End If**

**If storetree(L + 1, 16) > storetree(L, 16) Then**

**For i = 1 To 16**

**TMP = storetree(L + 1, i)**

**storetree(L + 1, i) = storetree(L, i)**

**storetree(L, i) = TMP**

**Next i**

**End If**

**Pivot = storetree(L, 16)**

**LP = L**

**RP = R + 1**

**Do**

**Do**

**LP = LP + 1**



```

    Loop While storetree(LP, 16) < Pivot
    Do
        RP = RP - 1
    Loop While storetree(RP, 16) > Pivot
    If RP <= LP Then Exit Do
    For i = 1 To 16
        TMP = storetree(LP, i)
        storetree(LP, i) = storetree(RP, i)
        storetree(RP, i) = TMP
    Next i
Loop
For i = 1 To 16
    TMP = storetree(L, i)
    storetree(L, i) = storetree(RP, i)
    storetree(RP, i) = TMP
Next i
If (RP - 1) - L < R - LP Then
    QuickL L, RP - 1
    QuickL LP, R
Else
    QuickL LP, R
    QuickL L, RP - 1
End If
End If
End Sub

Sub InsertL(L As Long, R As Long)
    Dim LP As Long
    Dim RP As Long
    Dim TMP(1, 16) As Double

    For RP = L + 1 To R
        For i = 1 To 16
            TMP(1, i) = storetree(RP, i)
        Next i
        For LP = RP To L + 1 Step -1
            If TMP(1, 16) < storetree(LP - 1, 16) Then
                For i = 1 To 16
                    storetree(LP, i) = storetree(LP - 1, i)
                Next i
            Else
                Exit For
            End If
        Next LP
        For i = 1 To 16
            storetree(LP, i) = TMP(1, i)
        Next i
    Next RP
End Sub

```

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## Vita

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